INTRODUCTION TO GEOLOGY

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PREFACE

The authors have been associated in teaching geology for more than two decades. During this time they have experimented with many different methods of presenting the introductory course and have had ample opportunity to observe the students' reactions while taking the work and their later opinions of the value of the subject matter. They have changed gradually the content of the beginning course from something of every phase of geology with explanations couched in somewhat technical terms to the outstanding principles of the subject with a minimum of technical phraseology.

Geology at its best offers a field for thinking and enjoyment and the beginner should not devote much time to memorizing data and becoming acquainted with terminology that is of little value after examinations have passed. The elementary student who is seeking mental training has the right to demand principles and geological reasoning rather than data that may soon be forgotten or confused. Most students have no intention of carrying their geological studies beyond the first course, and technical details tend to obscure the larger vision. As a matter of fact, the authors have observed that students who major in geology enter later courses with more enthusiasm and less feeling of repetition in subject matter if their first course is not technical.

In writing this textbook, the authors have kept before them the view that not more than one in every hundred of the readers will become a geologist. They have also thought of the text as a suitable broad foundation for later professional studies. The principles that have motivated them in the actual writing have been the selection of the most fundamental subjects and simple presentation. They have felt that it is not necessary to mention every phase of geology in order to give a broad survey of the field. They have kept in mind the outstanding need for a treatment of both physical and historical geology that may be mastered in a five-hour course of a semester's duration.

In preparing the text Tarr wrote the chapters on physical geology except The Work of Running Water, The Work of Snow and Ice, and Structures and Diastrophism. Branson wrote the historical part and the three chapters mentioned in the preceding sentence.

The sources of the illustrations have been acknowledged in the text, and where drawings have been modified the original drawings are mentioned. Particular mention should be made of the illustrations procured from the United States Geological Survey, the United States

Forestry Service, the United States Army Air Service, the United States Navy Air Service, the American Museum of Natural History, Professor S. W. Williston's books, Professor Charles Schuchert's paleographic maps, Professor W. B. Scott's works, Professor H. F. Osborn's works, and the recent textbooks by Professor Raymond Moore, and Professors Emmons, Thiel, Stauffer, and Allison. Most of the original drawings were made by Miss Coral Fleenor and she retouched the photographs where retouching was necessary. Miss Grace Carter rendered efficient service in typing the manuscript and various secretarial duties. Willard Bailey made many of the line drawings. Mrs. Vaona Peck, Wilford Cline, James Mitchell, Robert Clark, Trusten Peery, and Philip Morey prepared the outcrop maps.

Our colleagues Walter Keller, Raymond Peck, Carl Swartzlow, Sam T. Bratton, and John Quincy Adams have helped with the work by suggestions and discussions. Mrs. W. A. Tarr has been of invaluable service to Tarr. Branson is under heavy obligations to his colleague M. G. Mehl for help in many ways, and for his collaboration in some parts of the discussion of historical phases.

It is fitting to mention the teaching and books of S. W. Williston, Thomas C. Chamberlin, R. D. Salisbury, and Stuart Weller as having laid the foundation for this book. Perhaps the greatest debt of the authors is to their students who have shown them the way toward improvement in their selection and presentation of the materials.

E. B. Branson.
W. A. Tarr.

Columbia, Missouri,
March, 1935.

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PART I

PHYSICAL GEOLOGY

CHAPTER I

INTRODUCTION

Few sciences give the individual so much knowledge of the physical world about him as does geology. We are always in the presence of some of the features of which geology treats, such as hills, valleys, rivers, lakes, mountains, canyons, wind, ocean, rocks, or soil, and the person who understands the origin of these features will derive a deeper satisfaction from his surroundings. How few people look upon a beautiful stream winding its way through a valley bordered by rolling hills or rugged cliffs and see in it the agent that formed both the valley and the hills. Not knowing how a stream accomplishes its work, most people, while standing upon one of the hills along the valley, could not in imagination follow the stream back through its early stages and see the valley when it was a mere gully that slowly but surely grew to its present size. Why is there a precipitous bluff at a certain point by the stream while the valley, both up- and down-stream from the bluff, is bordered by gently rolling hills? Undoubtedly the character of the rock composing the bluff had something to do with it, but the person who knows nothing about the physical properties or composition of rocks cannot tell why a bluff was formed at just that point. Yet how much it would add to his appreciation of the forces of nature if he only knew that the rock forming the bluff was, for instance, volcanic in origin and once filled the throat of a volcano which has been entirely removed by the physical agents that are forever changing the surface of the earth. The inquiries might go further back, asking where this volcanic rock came from, how far down in the earth it was, what caused it to move outward, and what happened when it reached the surface. Geology seeks to answer all such queries.

But the questions could be carried still further back, inquiring how the earth originated, what was the source of the matter composing it, and whether it is like the other bodies that comprise the universe. These questions lead us into another realm of science, that of the astronomer; hence we may ask him for the answer to some of these queries. However, as geology treats of the earth, the geologist must help in answering the questions, for he knows about the composition, size, weight, and density of the earth's body, and these factors have a bearing upon its origin.

The discussion of the origin of the earth may be called *astronomic geology* because it makes use of both astronomy and geology.

As we travel about on the earth, we find rocks in layers or strata that are usually flat, though in some places they are inclined. Why? The geologic answer is that these rocks were formed by the deposition of muds and sands on the bottom of the ocean, and that earth movements have later caused any inclination of the strata. The study of the position of the rocks in the earth's crust we call *structural geology*. We note also that rocks are different in character, each kind with its own distinguishing features that enable the geologist to name the rock and make deductions as to its history. The discussion of the different kinds of rocks is known as *petrology* (from *petros*, meaning "rock," and *logia*, meaning "to learn of").

If we examine the stratified rocks somewhat in detail, we may find other features about which we should like information, a shell for example. It is embedded in the rock and has a fascinating story to tell, for it is evidence that life was in existence when the rock was formed. We should want to know about the conditions under which this life existed and what other creatures were on the earth at that time. The study of former life remains is known as *paleontology*, and the geologist trained in that field can give us a wonderful picture of the land and seas, the climate, and the life of early times upon the earth.

There are many other fields of study in geology, but even the short sketch just given shows that a knowledge of geology can contribute a great deal to the pleasure of understanding the world about us. This knowledge can be used everywhere: in the fields; upon the highway; on the ocean; even in the cities, for in them a vast amount of earth materials is utilized for our comfort and pleasure.

Geology deals with all the features of the earth's surface, and with the origin, composition, structure, and inhabitants of the earth. In this study some of the explanations will involve physical and chemical data, and others, biological. This makes possible a logical, twofold division of geology: one division is known as *physical geology*, *i.e.*, a treatment of the rocks composing the earth, the movements within it, and its surface features and the agents that form them; the other, *historical geology*, traces the changing distribution of land and seas upon the earth and gives the story of the life inhabiting it.

CHAPTER II

THE ORGANIZATION OF MATTER (OF THE EARTH)

The term *matter* is applied to the material that forms the planets, sun, stars, and everything on these bodies. All matter is composed of a relatively small number of substances called *elements*. We all are familiar with some of these elements, nine of which have been known since prehistoric times. These nine are copper, gold, silver, iron, lead, sulfur, mercury, carbon, and tin. Which one man knew first we do not know and never shall. Twenty more of the elements had been recognized by 1800, 51 during the nineteenth century, and 12 during the present century. This brings the number known to 92, which, it is believed, represents all the possible elements. The most fundamental unit of an element is the *atom*, the nature of which we shall consider briefly.

The Atom.—An atom is far too small to be seen by any means yet devised by man. It has been regarded as the smallest physical unit that can exist by itself, and as far as our present knowledge of the physical state of matter is concerned this may be true. Science, however, has been constantly pushing the borders of our knowledge downward to discover smaller and smaller units of matter, and outward to embrace larger and larger units in the universe, so who can say that in the atom we have the smallest unit of matter that can exist alone, or that there are limits in either direction? It will be sufficient, however, in our discussion of the organization of matter to consider the atom as the smallest unit and to leave any further division to the physicist and chemist.

The minuteness of atoms is inconceivable. It has been computed that every gram of water contains 600,000,000,000,000,000,000 (6×10^{20}) of them. Just what such a number means is beyond our understanding, but the following illustration may make clearer the small size of atoms. Water is composed of hydrogen and oxygen in the ratio of two hydrogen atoms to one of oxygen, and there are so many hydrogen atoms in one small drop of water that if each one of them in the drop was itself a drop of water there would be enough water to cover to the depth of one foot the surface of a globe the size of the earth. A human body of average size contains 10,000,000,000,000,000,000,000,000,000 (10^{27}) atoms. However small may be the size of atoms, it is of them, nevertheless, that the earth is built.

In our consideration of the organization of matter we shall regard the hydrogen atom as the smallest unit. It consists of a *nucleus* about

which revolves a tiny particle called an *electron.* Hydrogen is known as element number 1. All the other elements are built up from the hydrogen atom, the atom of each succeeding element having one additional electron revolving about its nucleus. Thus, the helium atom has two electrons, and helium is therefore element number 2. Lithium, which has three electrons, is element number 3. Iron is number 26, as its atom has 26 electrons; gold is number 79; and uranium, the last element, is number 92. Though hard to believe, it is true that rocks, clouds, living organisms, the air—in short, all substances—are composed of elements built up from this single unit of hydrogen.

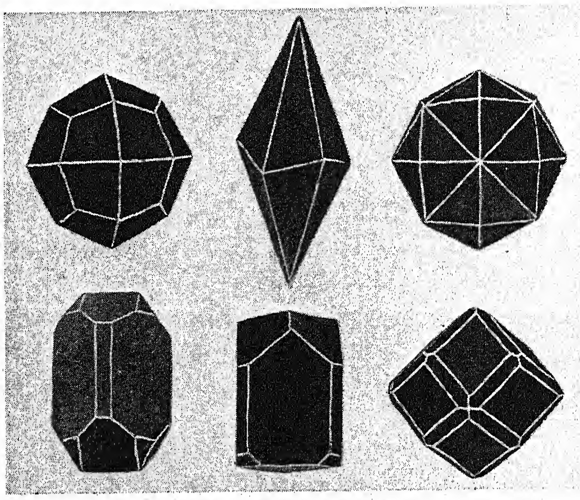


FIG. 1.—Wooden models of some perfect crystals.

As an illustration of the close relationship existing between elements two well-known ones, gold and mercury (quicksilver), will be considered. Everyone is familiar with gold, its color, weight, and other properties; and likewise with mercury, for it is in common use in thermometers and various other instruments. Mercury is heavy, 13.5 times as heavy as an equal volume of water; but gold is still heavier, being 19 times as heavy as water. These two elements, so vastly different in their various properties, are side by side in the table of elements, gold being number 79 and mercury number 80 in the series. Therefore, could one more atom of hydrogen be added to each gold atom, the gold would be converted into mercury; and, conversely, if one hydrogen atom could be taken from each mercury atom the mercury would change to gold. It has been the dream of man throughout the ages to be able to make the change from mercury to gold. But the energy necessary to do so would be enormous. Some chemists have shot the terrifically fast-moving particles given off from radium into mercury vapor and believed they succeeded

in knocking out hydrogen atoms and so producing gold. However, gold in such minute amounts could be detected only by the most delicate methods known. These brief statements illustrate the wonderful organization of matter and give some idea of how the elements are built up from a simple unit.

Matter may be *crystalline* or *amorphous.* In crystalline material the atoms have a definite arrangement (resulting in crystals, Fig. 1) which is independent of their size or shape. One of the wonderful features of this definite arrangement of matter is that *all known crystalline compounds* can be put into 32 classes. Furthermore, all the 32 classes

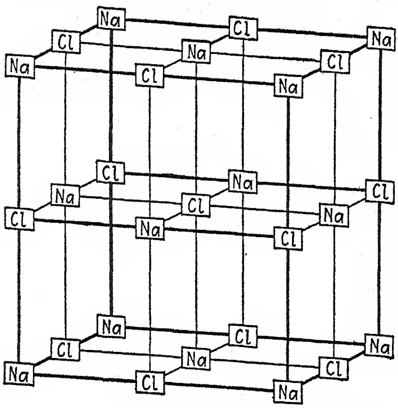


FIG. 2.—Drawing showing a possible arrangement of the atoms of sodium (Na) and chlorine (Cl) in a unit cube of salt (NaCl). In the other possible arrangement, the sodium atoms would change places with those of chlorine.

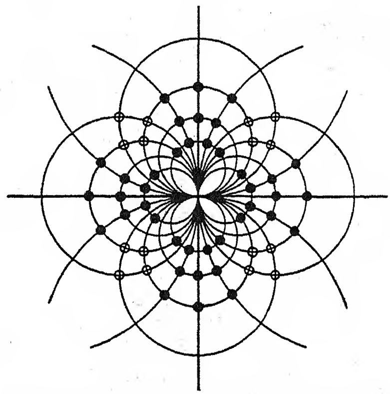


FIG. 3.—Sketch showing the position of the atoms in a crystal of salt, determined by passing X-rays through it. Note the four parts of the figure, comparable to the cubic structure of salt. Compare Fig. 2.

can be placed in 6 crystal systems. The marvelous simplicity of this arrangement is surprising, as there are thousands of crystalline compounds. In the study of these compounds it is now possible by passing X-rays through a crystal of one of them to determine the position of the atoms in the compound (see Fig. 2). The discovery that X-rays could be used to obtain a photograph (Fig. 3) of this arrangement was made in 1911, and since that time the use of this method has enabled us to understand fully the actual structure of many thousands of such compounds. *Amorphous substances* do not possess a definite arrangement of the atoms, yet the number of amorphous compounds and the different forms the material has assumed are many. A good example of a great group of amorphous compounds is the body of a living creature; in fact living matter of any kind belongs to this group.

Molecules.—The next (in size) units of which matter is composed are the *molecules.* These larger units result from the union of the atoms of one or more elements. Formerly, the molecule was of much impor-

tance in the discussion of chemical compounds as it was then thought to be the smallest division of matter. Present-day knowledge of the atom and its constituent parts relegates the molecule to the background, though the term is still used to represent a group of the atoms of one or more elements united as a compound: thus the molecule of water, consisting of two atoms of hydrogen (H) and one of oxygen (O), is written H_2O; sugar, $C_{12}H_{22}O_{11}$; salt, NaCl; and orthoclase feldspar, $KAlSi_3O_8$.[1] In a solid that is composed of a single element, as is iron (Fe), copper (Cu), or carbon, the molecule is built up of several atoms of that element. In our discussion of compounds we shall use the term "molecule" in this sense, *i.e.*, as representing an aggregate of the atoms of elements.

Minerals.—Certain aggregates of molecules are known as *minerals*. Most minerals are crystalline substances, but a few, of which the opal is an example, are amorphous. We shall define a mineral as *a naturally occurring inorganic substance having a definite chemical composition and definite physical properties.* Ice on a pond occurs naturally; it has a definite chemical composition, *i.e.*, one part oxygen and two parts hydrogen, H_2O; and it has the physical property of forming six-sided crystals (this property may be observed in a perfect snowflake). We conclude therefore that natural ice is a mineral. From our definition of a mineral it will be seen that water is equally well a mineral, though in the popular conception only solids are accorded that name.

Minerals are very abundant. The soil and all the rocks of the crust are composed of one or more of them. Minerals possess many different shapes, colors, and other physical properties. Many are beautiful, in both form and color, and so are eagerly sought after as ornaments and by collectors.

Composition of the Earth by Elements.—We have learned that all matter is composed of 92 elements. Most of these elements are so rare, however, that they have been seen by only a few people. Even such elements as platinum, gold, and copper are rare in that they form an insignificant part of the body of the earth. Our use of such substances today is made possible only by the fact that during the formation of the rocks conditions existed that favored the accumulation of these valuable metals into the deposits in which we find them.

We are reasonably certain that, through various geologic processes, rocks from depths of 10 to 12 miles have been brought to the surface of the earth. Chemical analyses of all kinds of these rocks from all parts of the world have been made and the results have been averaged. We are certain, therefore, that this average composition is representative of the composition of this thickness of the earth, which is known as the earth's *crust*. An additional thickness of 30 miles is sometimes included

[1] C stands for carbon; Na, sodium; Cl, chlorine; K, potassium; Al, aluminum; and Si, silicon. See also list of common elements on opposite page.

in the term "crust," but this lower part would be better known as the *subcrust*. By the use of the word "crust" it should not be understood that there is a solid layer over a liquid interior of the earth, for this is not true.

COMPOSITION OF THE EARTH'S CRUST BY ELEMENTS

Element	Percentage
Oxygen (O)	46.710
Silicon (Si)	27.690
Aluminum (Al)	8.070
Iron (Fe)	5.050
Calcium (Ca)	3.650
Sodium (Na)	2.750
Potassium (K)	2.580
Magnesium (Mg)	2.080
(Percentage of the 8 dominant elements	98.580)
Titanium (Ti)	0.620
Hydrogen (H)	0.140
Phosphorus (P)	0.130
Carbon (C)	0.094
Manganese (Mn)	0.090
Sulfur (S)	0.082
Barium (Ba)	0.050
Chlorine (Cl)	0.045
Chromium (Cr)	0.035
Fluorine (F)	0.029
Zirconium (Zr)	0.025
Nickel (Ni)	0.019
Strontium (Sr)	0.018
Vanadium (V)	0.016
Cerium (Ce), Yttrium (Y)	0.014
Copper (Cu)	0.010
Uranium (U)	0.008
Tungsten (W)	0.005
Lithium (Li)	0.004
Zinc (Zn)	0.004
Columbium (Cb), Tantalum (Ta)	0.003
Hafnium (Hf)	0.003
Thorium (Th)	0.002
Lead (Pb)	0.002
Cobalt (Co)	0.001
Boron (B)	0.001
Glucinum (Gl)	0.001
Total	100.000

The table above gives the average composition by elements of the earth's crust, as estimated by Clarke and Washington. It will be seen at once that only eight elements make up 98.58 per cent of the crust (Fig. 4).

It should be noted that of the most common metals in use only iron, aluminum, copper, zinc, and lead are included in this table. Less commonly used metals, such as manganese, chromium, nickel, tungsten, and cobalt, are present in the table, but gold, silver, and platinum are not. Their estimated percentages in the crust are as follows: silver, 0.000,000,4; gold, 0.000,000,1; and platinum, 0.000,000,008. Such quantities can scarcely even be called traces.

Formation of the Primary Minerals.—Minerals may form anywhere upon or within the earth's body, but it has been determined by careful study that those which formed first (the primary minerals) were formed from a liquid mass (lava) within the earth's crust. In such a mass the

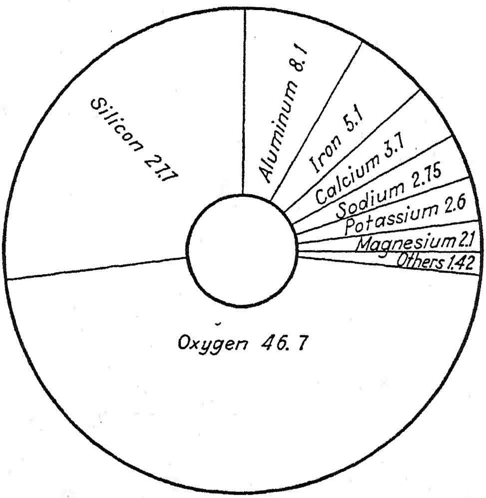


FIG. 4.—Diagram showing the relative percentage amounts of the eight most abundant elements of the earth's crust.

different elements were free to move about and unite with one another to form various substances. The rate of movement of the particles varied, being influenced by many factors. The most important of these factors were heat and the amount of water and gases present, as these two agents largely controlled the fluidity of the molten material. If the liquid was very thin, the particles could travel farther to unite; if it was very thick, like tar or asphalt, they could move only short distances. Such factors influenced the size of the mineral particles formed.

As indicated above, some minerals contain only one element. Gold, silver, sulfur, and carbon (occurring as the diamond and graphite) are examples, but these minerals do not play an important part in forming the rocks. The primary minerals form the rocks and so are the dominant minerals in the earth's body. The eight elements (oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium) that

comprise 98.58 per cent of the earth's crust (see above table) are the elements that formed the primary minerals.

These various elements were all mixed together in the liquid mass in which the primary minerals were formed. Oxygen, the most abundant of the eight elements, exists in the atmosphere as a gas, but it combines readily with the other seven elements (Fig. 5). These eight elements united to form many different primary minerals, some of which are simple in composition, as, for example, *quartz* (familiar to all as the dominant constituent of sand), which is composed of one atom of silicon and two atoms of oxygen, SiO_2. Because silicon ranks next to oxygen in amount in the crust, the compound SiO_2, commonly called *silica*, is very abundant. It readily united with other elements, and the resulting mineral is called a *silicate* because the silica is the basis of the compound, the other constituents varying. Aluminum, the third most abundant element in the crust, is a constituent of many of the silicates. The potassium, sodium, and calcium in the liquid mass united with silica and aluminum to form the most abundant group of primary silicate minerals, the *feldspars*. Two other common silicates, *hornblende* and *pyroxene*, were formed by making use of iron and magnesium. There are other silicates containing iron and magnesium, but they are less common than hornblende and pyroxene. The *micas* are two complex silicates that may also be formed as primary minerals. Thus the eight most abundant elements in the earth's crust united in various ways (Fig. 5) to form the following most important primary minerals, named in the order of their abundance: *feldspars*, *hornblende* and *pyroxene*, *quartz*, and *micas*.

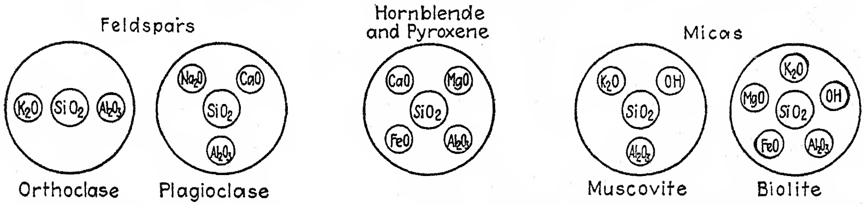


FIG. 5.—Diagram showing the composition, by molecules, of the feldspars, hornblende pyroxene, and the micas.

As the mineral molecules were forming within the molten mass, they united with one another, each one placing itself in a definite position relative to the other molecules like it. In this way a solid crystal of the mineral (Fig. 1) was built up. The external form of the crystal was determined by this internal arrangement of the molecules. The minerals are the "building blocks" of which we shall make use in the next chapter in explaining the formation of the rocks of the earth's crust.

CHAPTER III

VOLCANISM AND IGNEOUS ROCKS

INTRODUCTION

In the previous chapter it was pointed out that the study of minerals was a preliminary step to the study of rocks. *A rock is a substance composed of one or more minerals.* It may also be defined as *an essential part of the earth's crust.* Rocks that resulted from the solidification of a liquid mass (lava) were the first or *primary rocks*, and are known as *igneous rocks* ("igneous" comes from the Latin word *ignis*, meaning "fire"). The term *volcanism* is applied to the study of volcanic action. This chapter deals also with the source of lava within the earth, its movement, composition, solidification, and the final forms assumed when it becomes solid. The form and position of the solid igneous rock in the crust or at the surface are known as its *mode of occurrence.*

The igneous rocks owe their significant characteristics to two important factors: (1) *the composition of the original molten mass*, which controls what minerals will be formed upon solidification; and (2) *the conditions under which the mass cooled*, since the rate of cooling controls the size and arrangement of the mineral grains.

We shall begin our discussion with the consideration of a molten mass within the crust and follow it to its final stage, *i.e.*, the solid igneous rock.

THE MAGMA

A great mass of liquid rock within the body of the earth is commonly called a *magma*. It forms a supply from which the lava moves upward into the crust or to the surface. Figure 6 contains a sketch of such a magma lying about 10 miles below the surface. At this depth the magma is in the lower part of the zone in which fissures and joints exist in only the strongest rocks.

Source and Movement of a Magma.—A magma is formed by the melting of rocks within the earth due to the heat available there. For various reasons we are certain that temperatures within the earth are high. All deep wells and mines show an increase in temperature as they go deeper into the crust. Furthermore, from the lavas themselves we may learn of the high temperatures, as we can measure their heat as they come from volcanoes or can heat a solid piece of lava and determine its melting point. Both methods have been used and have shown

that the temperatures of lavas vary from 600 to 1200°C. Not all rocks, however, melt at the same temperature, some becoming liquid at low and others only at high temperatures. Many other factors influence the melting, but it is not necessary to consider them here.

The formation of a magma probably takes place in any portion of the earth's body where the temperature is high enough to melt the rocks. This melting may occur 10, 50, 100, or 500 miles down. The liquid rock may then work its way upward to the crust or the surface by melting

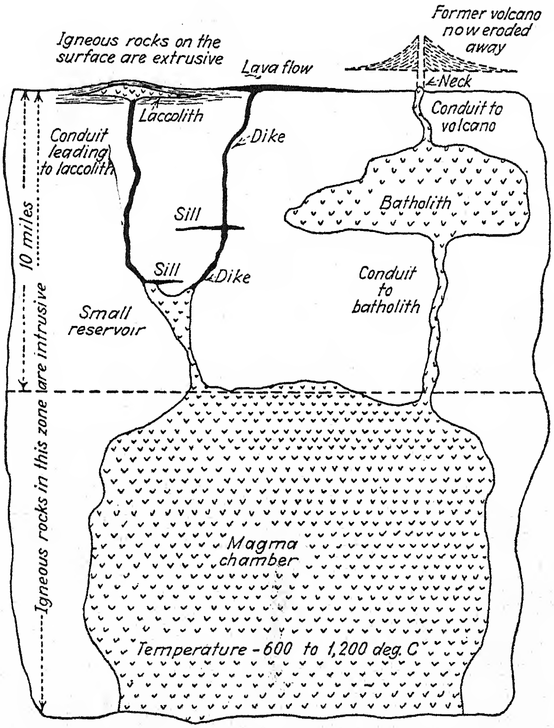


FIG. 6.—Sketch of an ideal magma and the various forms of igneous rocks connected with it.

the rocks above it. Liquid rock is lighter in weight than solid rock and the presence of gases makes it still lighter. Therefore, as the magma is subjected to great pressures (about 1,200,000 pounds or 600 tons per square inch at a depth of 200 miles) from the surrounding solid rocks, it is forced to move, and the movement is upward because that is the direction of least pressure. The movement is aided by the great mobility of liquid rock and also by the expansive force of the gases within the magma. Figure 7 illustrates this upward course of a magma. A steady loss in heat and consequently in volume accompanies this upward movement of the magma, and thus when the mass comes so near the surface that it no longer has sufficient heat to melt its way upward it comes to

rest, and assumes many different forms, as shown in Fig. 6. From the upper part of the magma, portions rich in gases may find local weak places in the crust and work their way on upward, some even reaching

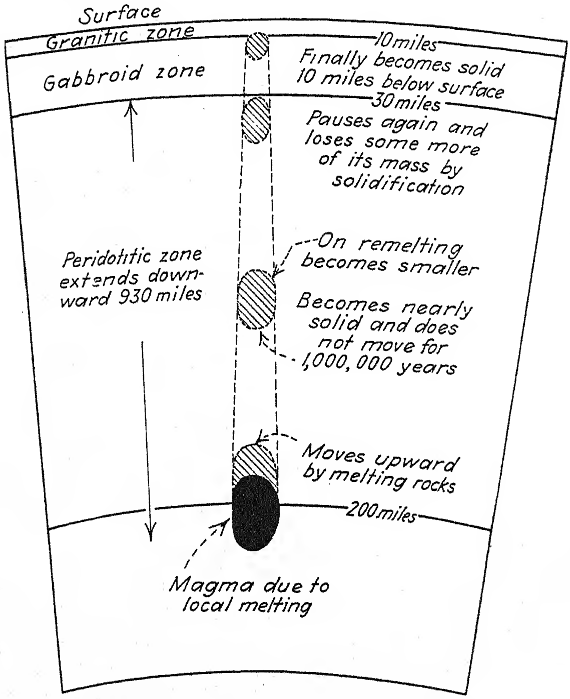


FIG. 7.—Sketch of a magma working its way to the surface.

the surface. After the magma has reached the upper zone of cracked and fissured rocks, an additional method of upward movement is available to it, it may pry off blocks of the solid rock from the roof of the magma

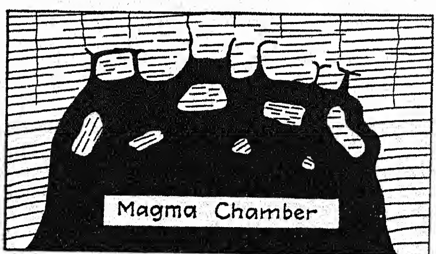


FIG. 8.—Sketch showing the magma (black) prying off blocks of the surrounding rock by wedging into the cracks and fissures.

chamber (Fig. 8). These blocks, being heavier than the liquid lava, sink into it and so cause the lava to move on upward. In this region of cracks and fissures the lava will also move out into these openings, where

it is possible for it to force the cracks still wider apart because by its pressure on their walls the cracks and joints in the adjoining rock will be reduced in size, perhaps even practically closed. Room may thus be made in joints and other openings for a considerable body of lava to pass, and finally perhaps to solidify.

The heat of a magma may be sufficient to keep it in a liquid state for many thousands of years, during which time it may act as a source from which material moves outward from time to time to feed a volcano. Gases, by reacting with one another, may play an important part in the maintenance of this heat and in the accompanying volcanic activity.

Composition of the Magma.—The composition of magmas varies in different parts of the earth, but geologists believe that, in the main, magmas occurring to depths of 10 miles are of one type, those that are 10 to 40 miles (the maximum thickness of the crust) down are of another type, and those in the layer (approximately 900 miles thick) next below the crust are of still another (see Fig. 7). These three regions of the earth's body are known as the *granitic, gabbroid or basaltic*, and *peridotitic zones*. A magma that had moved upward from a lower into a higher zone would have the composition of the lower one; but, as it melted and mingled with the rocks above, its composition would change.

We have given on page 7 the average composition of the rocks of the earth's crust. It has been estimated that 95 per cent of the crust is composed of igneous rocks, and therefore the average composition of the crust is approximately the composition of the igneous rocks. As has been pointed out also (page 8), only a few of the elements are of importance in forming the rocks. Variations in the amounts of these significant elements give rise to different kinds of rocks. Thus an abundance of iron, magnesium, calcium, and less than 60 per cent of silica gives rise to the gabbroid and the peridotitic rocks; and an abundance of silica, and aluminum, potassium, and sodium, to the granitic rocks. Between these two types there are all gradations.

The composition of a magma governs what minerals will be formed from it and also has a marked influence upon its movement. The basaltic lavas are more fluid than lavas rich in silica and consequently will squeeze into smaller fractures or joints in the rocks or flow farther on the surface. The fluidity of magmas influences the size of the mineral grains formed, as will be explained later. The presence of water (as a liquid or gas) and other gases in the lava greatly increases the fluidity. It should be noted in this connection that very little of the water and gases of the magma becomes a part of the igneous rock, as they are separated from the magma during its solidification. If this solidification occurs on the surface, the water and gases escape into the atmosphere, but if it occurs below they enter the surrounding rock, carrying with them much mineral matter and any metals the magma contained. These

minerals and metals may later form the valuable mineral (ore) deposits from which we obtain such metals as gold, copper, and iron. These deposits will be discussed later in this chapter.

Solidification of the Lava.—The solidification of a lava is influenced by (1) *the rate at which it cools* and (2) *its composition.*

The Effect of the Rate of Cooling.—We have noted the wide variance in the temperatures of lavas: from 600 to 1200°C. There is a steady decrease in heat as a lava moves upward, and when it comes to rest the heat passes into the surrounding rocks and is lost. The rate at which the cooling takes place varies, and depends upon many factors of which the following are the most important:

a. Depth of the mass below the surface.
b. Size of the cooling mass.
c. Shape of the cooling mass.

a. The depth of a magma below the surface is of primary importance in the rate of cooling. A mass near the surface undoubtedly loses its

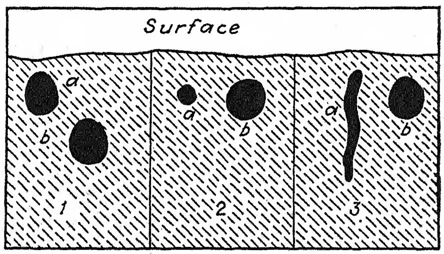


FIG. 9.—Sketch illustrating some of the factors that affect the rate of cooling of lava (black areas).

heat much faster in the cooler area than does one that is twice as deep (Fig. 9, 1, *a* and *b*) and so becomes solid much sooner.

b. Of two similarly shaped lava masses at the same depth (Fig. 9, 2, *a* and *b*), one that is twice as large as the other takes much longer to cool and so solidifies much more slowly than does the smaller one.

c. If one mass of lava has a spherical shape (Fig. 9, 3, *b*) and another is thin and tabular (Fig. 9, 3, *a*), the thin one certainly loses its heat faster.

The rate of cooling of a magma greatly influences the size of the mineral crystals formed during the solidification. Slow cooling keeps the magma fluid for a long period of time, which permits more molecules to get together and form large crystals; rapid cooling means small crystals; and extremely rapid cooling, such as occurs when a thick viscous lava pours out upon the surface, prevents the formation of any grains, and a glassy rock is the result.

The Effect of Composition.—The composition of a magma affects its fluidity, and this fluidity, as we have already noted, becomes significant during solidification as it influences the ability of the molecules to get

together to form minerals. In a thin (*i.e.*, very fluid) basaltic lava the molecules can travel much farther during the period of cooling and therefore more of them can get together to form larger grains or crystals. The presence of much water, carbon dioxide, sulfur dioxide, and other gases increases the fluidity of a lava and so is favorable to the formation of large grains; in fact, the presence of these substances is so helpful in forming large mineral crystals that they are called *mineralizers*. The mineralizers are important, also, in forming deposits of valuable metals.

TEXTURE OF IGNEOUS ROCKS

We have seen how the various factors influencing the solidification of a magma combined to produce solid rocks having grains of different

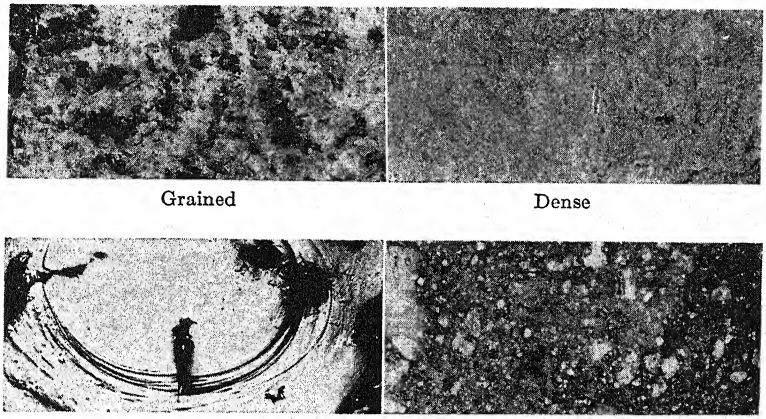


FIG. 10.—The principal textures of igneous rocks.

sizes. *The size of the grains, together with their arrangement in a rock, is called texture.*

Different Kinds of Texture.—It is possible to divide rocks into four classes based upon their texture, *viz.*, *grained*, *dense*, *glassy*, and *fragmental* rocks. The lines dividing the first three classes are purely arbitrary. For our purpose we shall consider the *grained rocks* as having mineral grains or crystals larger than those of fine granulated sugar (about 1/16 inch in diameter); the *dense rocks* as those with mineral grains ranging from 1/16 inch in diameter to those that are invisible to the naked eye; and the *glassy rocks* as those that are devoid of grains. Figure 10 illustrates these three textures. *Fragmental* texture is not due to solidification, but to the fact that a rock is composed of fragments (see Figs. 10 and 11), which in the case of the igneous rocks were blown from a volcano.

A special feature of the texture of igneous rocks, but a very common one, is that the crystals of the same rock may be of two general sizes (see Figs. 12, and 54 on page 44). This type is called *porphyritic*

texture and the rock is called a "porphyry." This texture is usually the result of two periods of cooling in the magma. The first period occurred at a considerable depth, where the slow rate of cooling permitted certain minerals to grow to considerable size. Then the lava containing these solid crystals was forced up nearer the surface, where the still-liquid portion solidified rapidly, forming a fine-grained rock in which the earlier, larger crystals were embedded. The large crystals in a porphyry are called *phenocrysts* and the background of uniformly sized particles is called the *groundmass*.

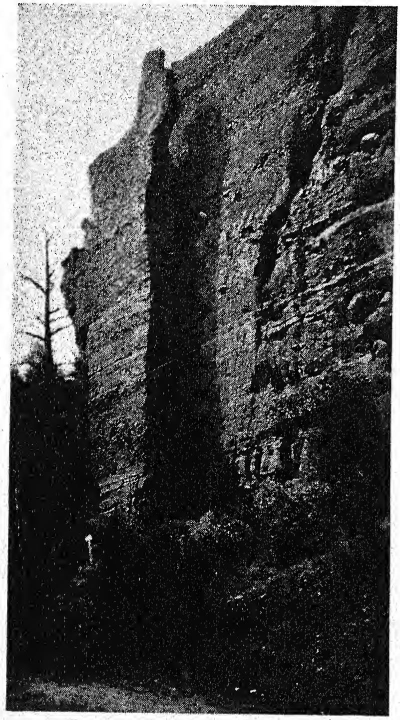


FIG. 11.—Fragmental texture in volcanic breccia, on road between Cody, Wyoming, and Yellowstone National Park. (*Photograph by Edwin R. Branson.*)

MODE OF OCCURRENCE OF IGNEOUS ROCKS

Study of the forms of igneous rock masses has shown that the openings followed by the lavas in their upward journey are of two dominant types: *tubular* and *tabular*. Tubular openings are rudely circular in outline, and most of them are less than a mile across but some greatly exceed this width. Such an opening, called a *conduit*, is the usual one leading up to a volcano and certain intrusive forms. The tabular type of opening is usually an enlarged fissure or joint in the rock. Some are miles in length but usually much less than a mile in width. Such openings are called *fissure openings*.

Igneous rocks have two major modes of occurrence, *viz.*, *intrusive* and *extrusive*. Intrusive rocks are those formed by the solidification of a magma below the surface; and extrusive rocks, those formed after the lava reached the surface. Many different shapes were assumed as the magma or lava solidified, and these various shapes are commonly known as *forms*. The form of an igneous rock may be due to the shape of the opening (for example, tabular) the lava made for itself; to the melting of the enclosing rock; or it may be a surface feature. We shall describe in detail some of the more common forms of igneous rocks.

INTRUSIVE FORMS OF IGNEOUS ROCKS

The various intrusive types of igneous rocks and their relationship to the magma, to one another, and to the surface are shown in Fig. 6,

page 11. The more common intrusive forms are *dikes, sills, laccoliths, necks* or *plugs,* and *batholiths,* though geologists recognize many other special forms.

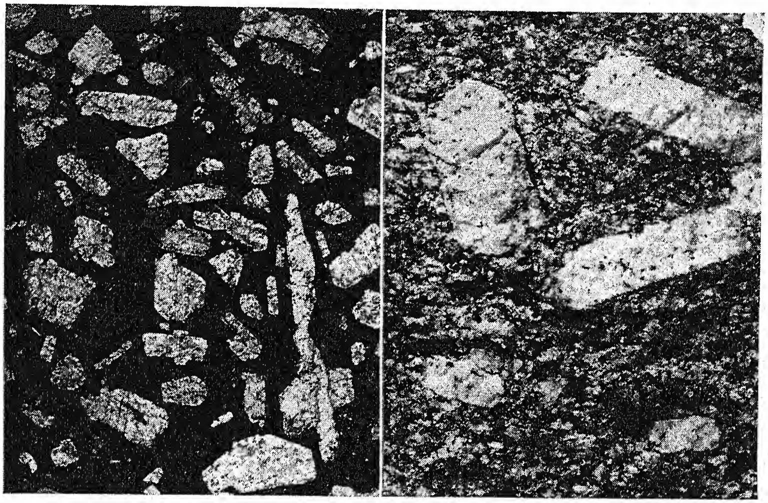
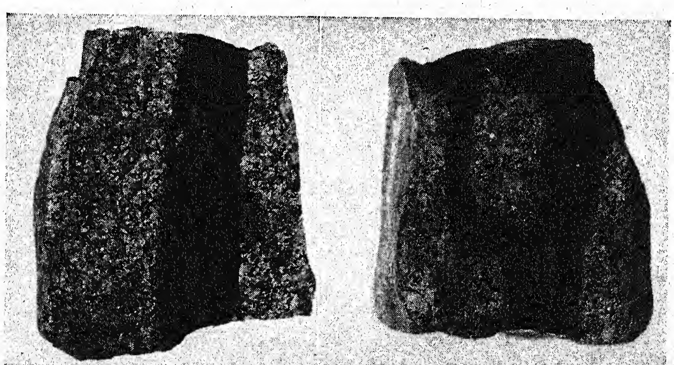


FIG. 12.—Porphyry (on left) with dense groundmass, from dike in Madison County, Missouri; porphyry (on right) with grained groundmass, from Connecticut.

Dikes.—Dikes are thin, tabular, parallel-walled masses of igneous rocks (see Figs. 13, *a* and *b*, 14, 15, and 16). They have essentially a vertical position, and were formed by being injected into fissures and



(*a*) (*b*)

FIG. 13.—Basalt dike in granite from southeastern Missouri. (*a*) Front view; (*b*) back view showing inclusion of granite in dike.

joints in rocks. Those occurring in sedimentary rocks usually cut across the bedding planes. Some dikes are no thicker than a sheet of paper, some have a thickness of hundreds of feet, but the vast majority are less than 10 feet thick. They may be miles in length. Dikes are the most common form of intrusive igneous rocks seen at the surface. They occur

in great abundance in many areas, especially in the vicinity of volcanoes. There are, for example, hundreds of dikes around the Spanish Peaks in southern Colorado (Fig. 17).

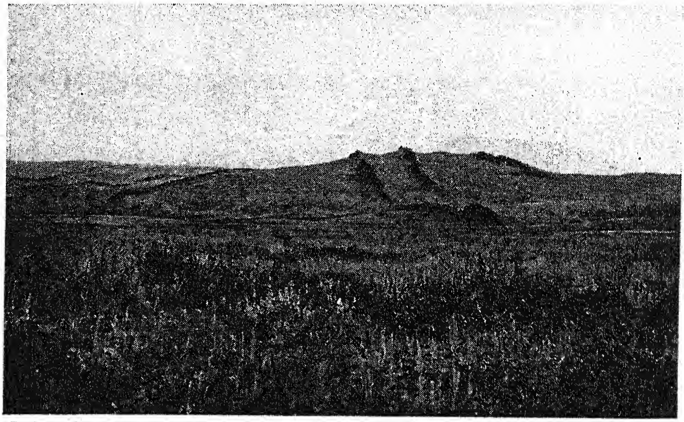


Fig. 14.—Dikes in the Highwood Mountains, central Montana. (*Photograph by W. A. Tarr.*)

Sills.—Sills also are tabular masses of igneous rocks, but their position is essentially horizontal. Sills are thickest over or adjacent to the opening through which they are fed and they thin out laterally. In very large sills the top and bottom are essentially parallel. Sills are formed by the squeezing in of lava between the beds or bands of a rock. They may cross the beds from one plane to another (Figs. 18 and 19). Like

Fig. 15.—Near view of one of the dikes in the Highwood Mountains, Montana. (*Photograph by W. A. Tarr.*)

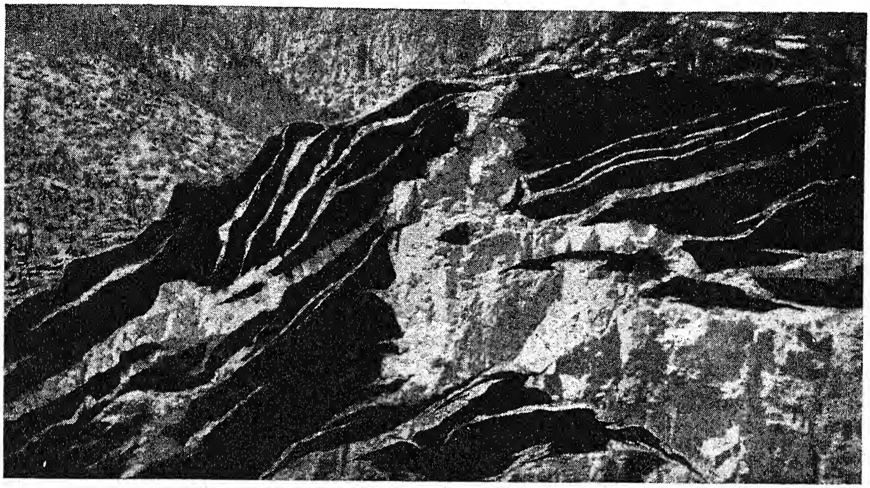


FIG. 16.—Granite dikes (light) intruded into schists (dark), Big Horn Canyon, Wyoming. (*Photograph by E. B. Branson.*)

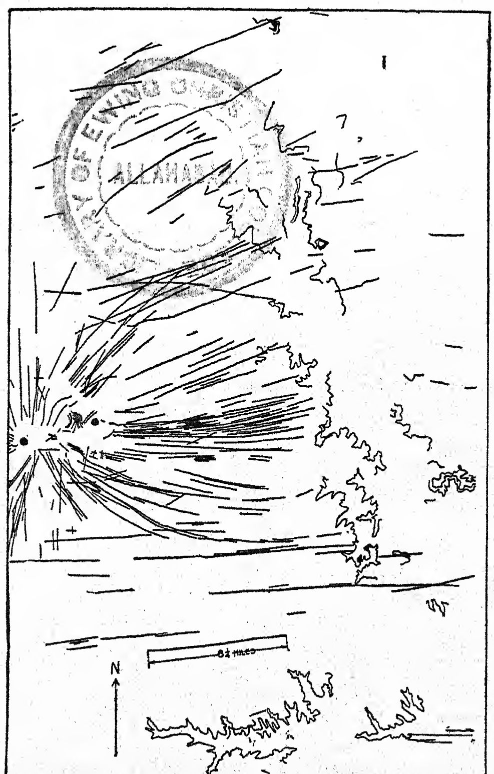


FIG. 17.—Map showing some of the dikes (straight lines) and sills (irregular lines) around the Spanish Peaks, Colorado. Black dots indicate East and West Spanish Peaks.

the dikes, sills have a wide range in size and extent. Most sills are thin sheets, though some are hundreds of feet thick and many extend over a horizontal area hundreds of square miles in extent as it is estimated

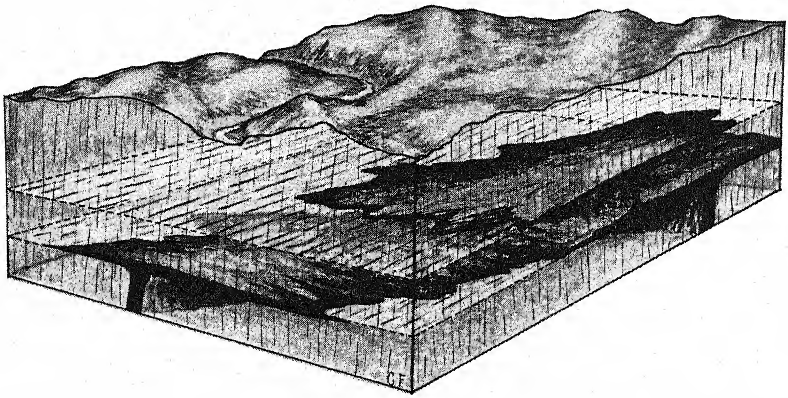


Fig. 18.—Sketch of sills fed by dikes. Note that a sill is thickest over the dike.

some do in South Africa. Opposite New York City the Hudson River exposes a thick sill, known as the Palisades of the Hudson.

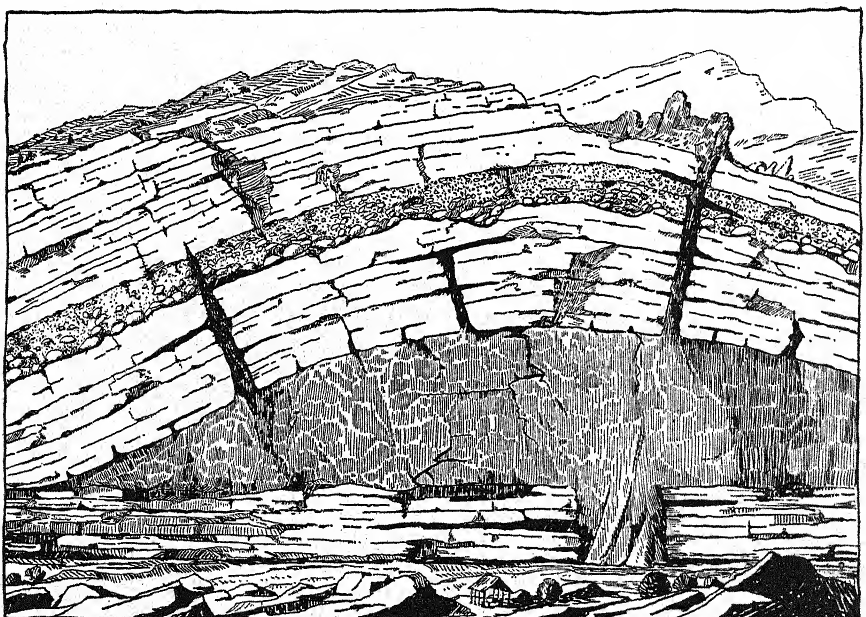


Fig. 19.—Sketch of an ideal laccolith and associated dikes and sills.

Laccoliths.—Laccoliths, though somewhat similar to sills (see Figs. 6 and 19), differ from them in that the overlying beds are arched. The horizontal area occupied by a laccolith is usually smaller than that

occupied by a sill. This is because the lava forming a laccolith was too viscous to flow far between the beds of the rock and so pushed them up

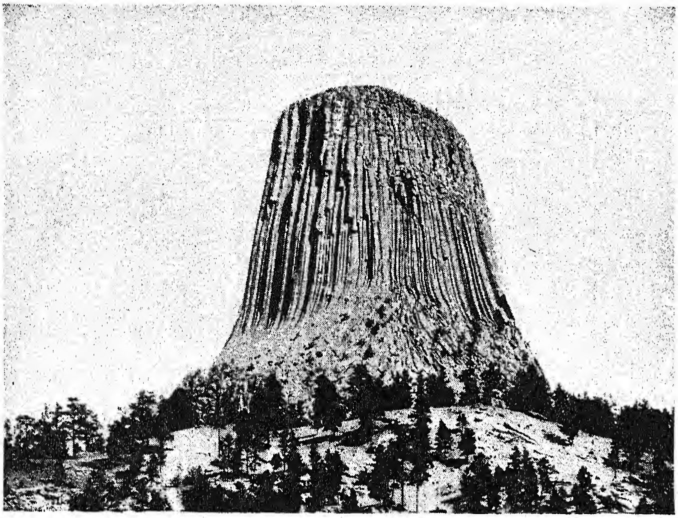


FIG. 20.—A volcanic plug (called Devils Tower) showing columnar structure. (*Darton, U. S. Geological Survey.*)

to form a dome. A laccolith is usually fed through a conduit (see Fig. 6). Laccoliths may merge into sills and they are also commonly associated

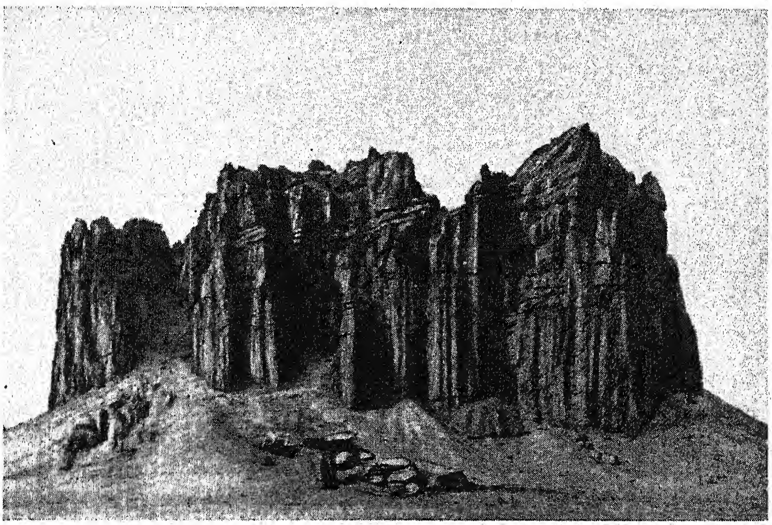


FIG. 21.—Ship Rock, an unusual type of volcanic plug in northwestern New Mexico. (*Photograph by E. B. Branson.*)

with dikes. Several laccoliths may occur in the same area. They form numerous buttes and mountains in western United States. Bear Butte

in the northern part of the Black Hills and the Henry Mountains of southeastern Utah are such examples. The laccoliths forming the Henry Mountains were the first of the type to be recognized and described.

Necks or Plugs.—Necks or plugs are circular masses of igneous rock having a vertical position. They occupy the conduit through which the lava of a volcano, laccolith, or batholith moved upward. When movement ceased, the lava still in the conduit became solid; and, after erosion had cut away the overlying mass of rock, this rock was exposed. This method of origin explains the name "neck" or "plug." These forms are numerous in some areas where volcanoes and laccoliths were formerly abundant. A striking example of such a feature occurs in northeastern Wyoming, where a high column of rock known as the Devils Tower rears itself 600 feet above the surrounding country (Fig. 20). A rock known as Ship Rock (Fig. 21) in northwestern New Mexico is a plug or neck composed of fragments of rock that were forced upward through a conduit as a solid column.

Batholiths.—Batholiths are very large (at least 40 square miles in area), irregular masses of igneous rock (see Fig. 6). They are formed by a magma's melting the rock in place and by its displacement of the rock. Exceptionally large batholiths (as that forming the Sierra Nevadas and one in central Idaho estimated to have an area of 20,000 square miles) may have been the original magmas themselves, which had worked their way upward into the crust. Pikes Peak, which has been carved from a batholith of granite, is an example that may be viewed by many. The world-famous copper deposits of Butte, Montana, occur in a batholith covering about 2,000 square miles. Many other valuable metal deposits are associated with batholiths. Batholiths are of common occurrence in all parts of the world.

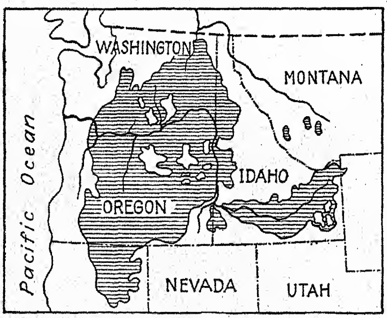


FIG. 22.—Map showing areas of lava flows in northwestern United States. (*Based on data from various sources.*)

EXTRUSIVE FORMS OF IGNEOUS ROCKS

If a lava in working its way upward from the magma has sufficient heat and pressure, it reaches the surface and becomes an extrusive igneous rock. The two common modes of occurrence of extrusive igneous rocks are *lava flows* and *volcanoes*. Lava flows generally rise through fissures and usually cover wide areas; volcanoes are fed through conduits and are much more restricted in extent. Volcanoes are the spectacular manifestations of volcanism and are the only form man has been permitted to witness. At that, he is often an unwilling spectator.

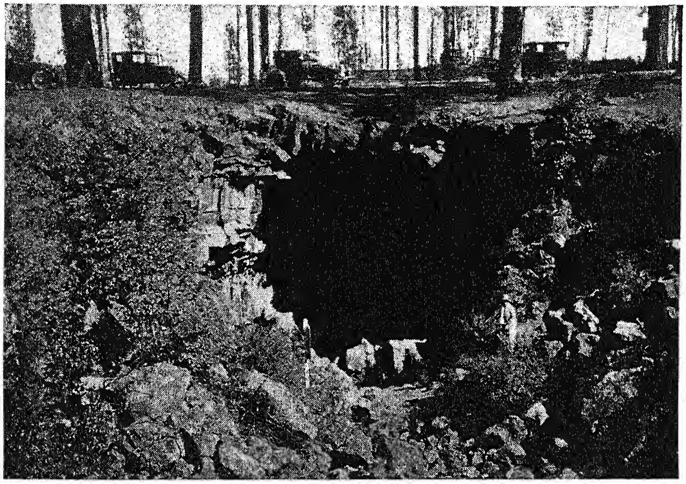


FIG. 23.—Entrance to lava cave south of Bend, Oregon, on Highway 97. (*Photograph by W. A. Tarr.*)

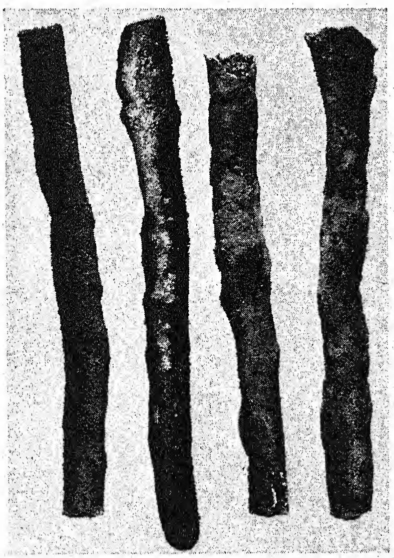


FIG. 24.—Stalactites of lava from lava cave near Bend, Oregon. One-half natural size.

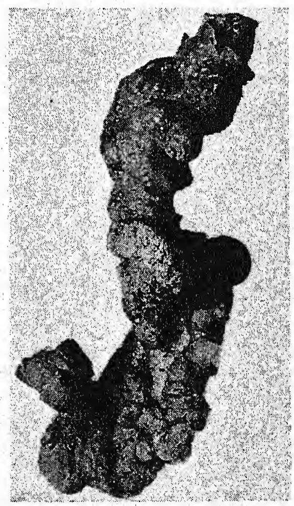


FIG. 25.—Another type of lava stalactite from lava cave near Bend, Oregon. One-half natural size.

Through studies of active and recent volcanoes we have learned much about the characteristics and composition of lavas, and by witnessing volcanic eruptions we are permitted a startling view of the effect of the tremendous forces within the earth.

Lava Flows.—In many regions the only rock in evidence over vast areas is that of lava flows. Some flows, as those of Idaho and Iceland, are so recent as to have no vegetation upon them; others are very ancient and are covered with soil and vegetation. In forming large flows the lava breaks through the crust along fissures miles in length, and enormous quantities are poured out and spread far and wide over the land. Such eruptions are relatively very quiet. In northwestern United States

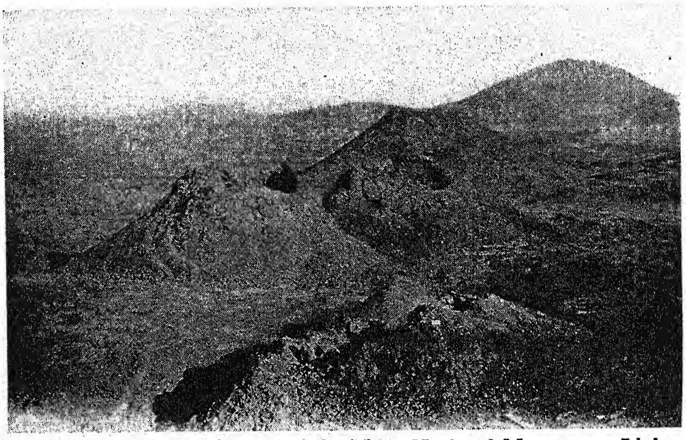


FIG. 26.—Spatter cones in the Craters of the Moon National Monument, Idaho. Distant hills are cinder cones. (*Photograph by W. A. Tarr.*)

(in Washington, Oregon, Idaho, and northern California) approximately 200,000 square miles of surface are covered by lava flows (Fig. 22) which, in places, are 3,000 feet thick. This lava poured out upon and buried a region of hills and mountains. The solidified lava occupying the fissures through which eruption took place is now visible as dikes where rivers have cut down through the lava flows. Other great lava flows are found in Iceland and on the Deccan plateau in western India. Small lava flows may accompany volcanic action.

Features of Lava Flows.—Recent lava flows show many features of interest. *Lava caves* are of common occurrence, and have an interesting origin. The surface of a lava flow was the first part to cool and solidify, of course, so a crust was formed under which the still-liquid lava below continued to move forward. All of the flow gradually became cool and consequently solid; but, as more lava continued to well up from below, it followed the old channel the lava had maintained under the crust, and when the supply from below was exhausted the lava in these channels drained out (just like water from a hose) leaving an underground passage

or cave (Fig. 23). Small stalactites (Figs. 24 and 25) of lava occur in the interior of some of these caves.

On the surface of some lava flows, small cones called *spatter cones* (Fig. 26) were built up where the lava broke through the crust and piled up about the opening. Otherwise smooth surfaces of lava flows may be broken by *ridges*, which consist of blocks of lava that resulted from the buckling up and breaking of the crust as the lava beneath it continued to move forward. The lava of very rough, jagged surfaces is known as *clinkery* (or *aa*) *lava*. Some surfaces consist of twisted, rope-like masses (Fig. 27), called *ropy lava* (or *pahoehoe*). The twisting was caused by the forward movement of an already viscous crust. Lava also assumes a

FIG. 27.—Ropy lava in the crater of Vesuvius, Italy. Pillowy lava in background. (*Photograph by W. A. Tarr.*)

pillowy surface (Fig. 27). Fine examples of these various types of lava, lava flows, and small volcanoes are to be seen in the Craters of the Moon, a national monument in Idaho (Fig. 28), and in numerous other places in western United States.

Volcanoes.—Volcanoes have long been a source of trouble to man because he has persistently sought to live upon or near them, an act that simply invites trouble. There is no natural phenomenon that is more awe-inspiring than a volcano in vigorous eruption. The earth movements, explosions, dust and ashes, and fiery lava are sufficient to satisfy the most avaricious thrill seeker. Detailed descriptions of eruptions cannot be given here, but accounts of Pelée in the West Indies (1902),[1]

[1] E. O. HOVEY, The Eruptions of 1902 of La Soufrière, St. Vincent, and Mt. Pelée, Martinique, *Amer. Jour. Sci.*, vol. 14, pp. 323–328, 342–349, 1902.

Vesuvius in Italy (1906),[2] and Katmai in Alaska (1912)[3] are readily available in libraries and are fascinating reading.

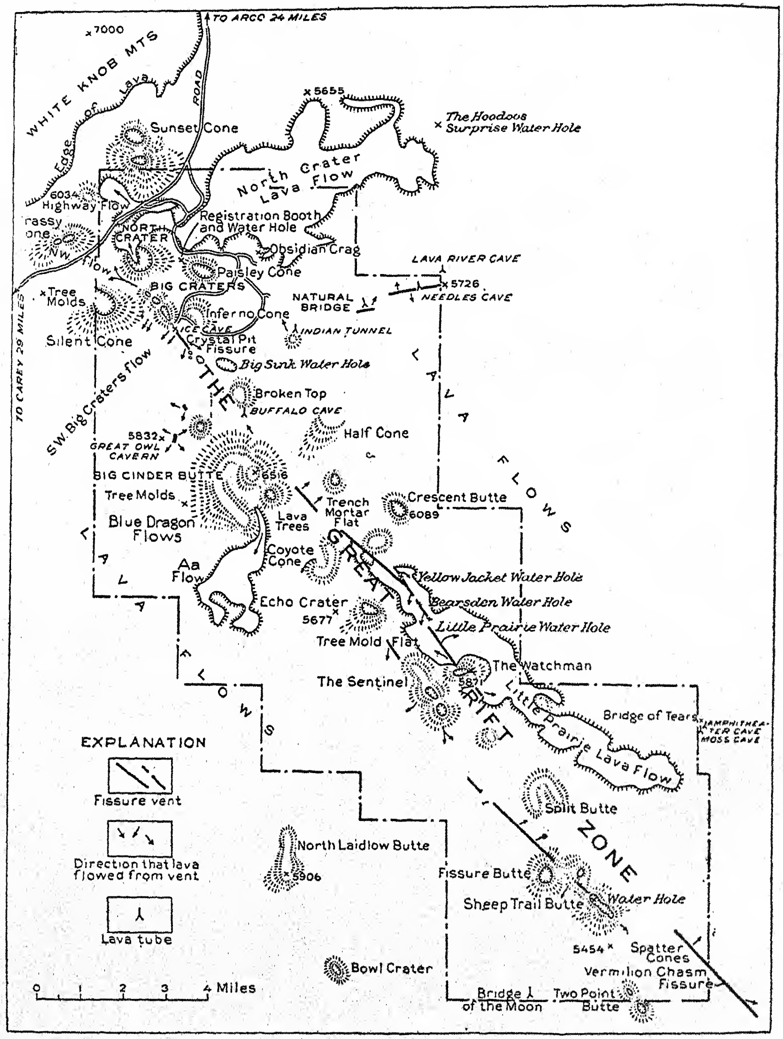


FIG. 28.—Sketch map of the Craters of the Moon National Monument, Idaho, showing location of the fissure (the Great Rift Zone) through which the lava was extruded. (*Idaho Bur. of Mines and Geol. Bull.* 13, *pl. I*, 1928.)

Character and Source of Volcanic Phenomena.—A volcano is the opening of a circular conduit about which have been or are being piled the lava and volcanic dust ejected through the conduit. The ejected

[2] FRANK A. PERRET, "The Vesuvius Eruption of 1906," *Carnegie Inst., Pub.* 339, 1924.

[3] ROBERT F. GRIGGS, "The Valley of Ten Thousand Smokes," National Geographic Society, Washington, 1922. (Contains 340 pages, 9 maps, and 233 illustrations.)

material forms a conically shaped hill or mountain (Figs. 26 and 29), and the depression in the top of the cone is known as the *crater* (Figs. 29 and 30) of the volcano. The range in size of volcanoes is great; many

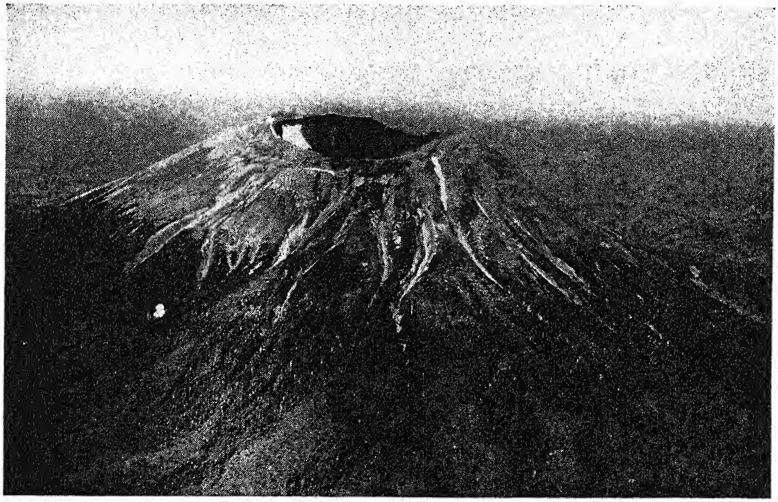


FIG. 29.—Air view of an Alaskan volcano. Crater well shown. (*Courtesy of U. S. Navy Air Service.*)

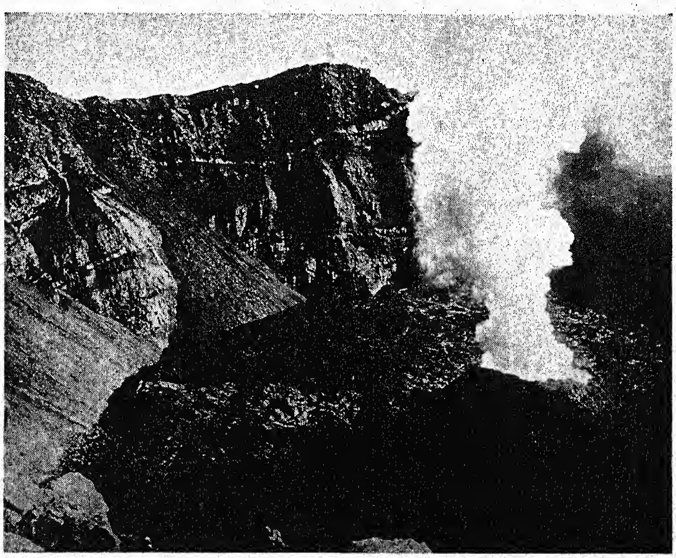


FIG. 30.—Interior of crater of Vesuvius, February 15, 1925. Shows lava floor and small active cone. Note edges of sills in crater walls.

are only a few hundred feet high; others tower more than 20,000 feet above sea level. Some have steep sides (the slope near the top of Mt. Vesuvius is nearly 50°), and others have gentle slopes. For the most

part the structure of volcanoes is similar. They are formed of successive lava flows or of lava flows and dust beds (Figs. 30, 31, and 32). These layers may be cut by dikes which formed where the lava broke through fissures in the sides of the volcano.

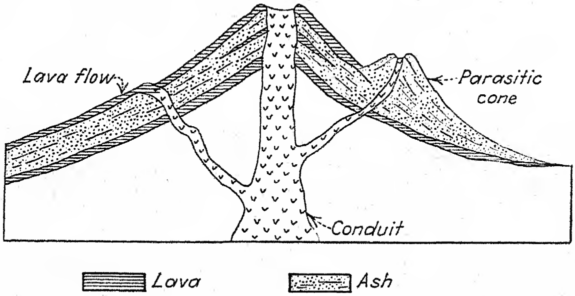


FIG. 31.—Diagram showing structure of a volcano and method of forming parasitic cones and lava flows.

Volcanoes represent a final form of lava that has reached the surface from a magma below. The magma that feeds a volcano may be large or small; it may be within two or three miles of the surface or at a considerable depth below it. A study of volcanic eruptions has shown that

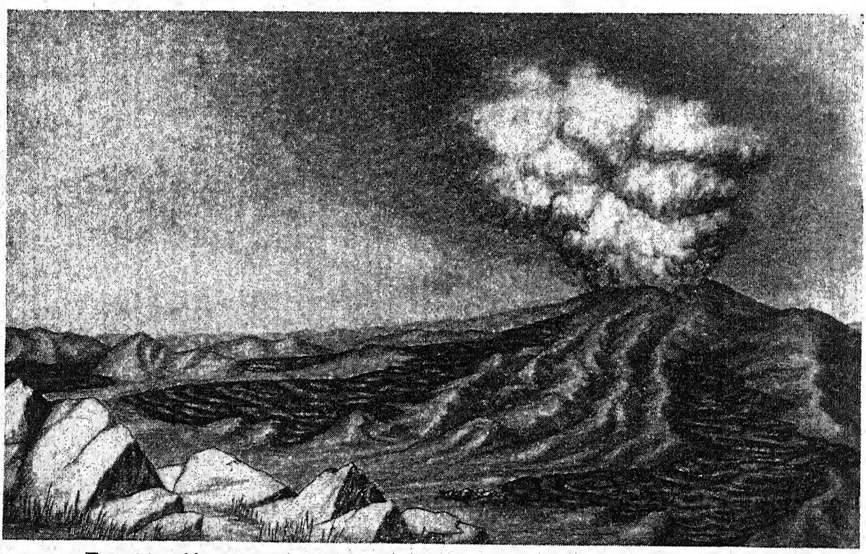


FIG. 32.—Sketch of lava flowing out through the sides of a volcanic cone.

adjacent volcanoes may or may not be fed by the same magma. The two great Hawaiian volcanoes Mauna Loa and Kilauea are only 22 miles apart and the crater of Kilauea is about 10,000 feet lower than that of Mauna Loa, yet sometimes the two volcanoes erupt independently. Sometimes, however, they erupt simultaneously, and a careful study of

the character of their lava and other features has not made it possible to decide whether they are fed by one magma or two, as all their features and characteristics may be explained by either mode of origin.

The temperature of volcanic lavas is high: from 900 to 1200°C. or higher. Some volcanic lavas are very viscous, but many are quite fluid and may be able to flow for miles. The motion-picture camera has given to the world at large a very clear idea of lava in motion as it poured out of Mt. Etna in Sicily during the eruption of 1928. Some lavas are accompanied by large quantities of steam and other gases, and some are not. The presence of water (as steam) in the lava has a marked effect upon the eruption of a volcano; if the quantities are large the volcano is usually of the explosive type as the rapid escape of the steam causes explosions. If small quantities of steam are present the lava usually wells up quietly to the crater and flows down the sides while the steam escapes and condenses, forming the enormous cauliflower-like clouds (Figs. 33 and 34) that hang over such a volcano. Numerous gradations exist, of course, between these two types of volcanoes. If the lava is quite viscous a volcano may remain quiet for long periods of time during which the gases accumulate at some point below the crater and when their pressure has become sufficient the top of the volcano is blown off (Fig. 35). This is what happened at Vesuvius, in A.D. 79 when Pompeii and Herculaneum were buried under many feet of volcanic dust and mud.

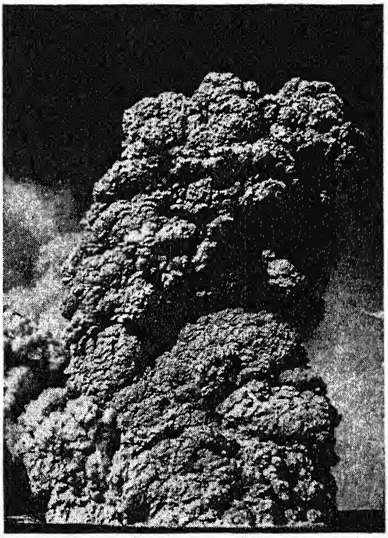


FIG. 33.—Cloud (4,000 feet high) formed by a blast of steam from Halemaumau fire pit in crater of Kilauea, Hawaii, May 24, 1924. (*Photograph by K. Maehara.*)

It has been possible to study the gases that are associated with lavas by collecting and analyzing those that escape from volcanoes. Water (steam) is by far the most abundant, but carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), chlorine (Cl_2), and also other gases are given off. Considerable amounts of some of these gases make the fumes ejected from a volcano extremely poisonous. Clouds of hot, poisonous gases have swept down upon towns and cities near volcanoes and snuffed out the lives of thousands of people in a few seconds, as happened at St. Pierre at the foot of Mt. Pelée on the island of Martinique in 1902 (see Fig. 47 page 39).

Features Produced by the Escape of Gases from Volcanic Lavas.—The gases of volcanic lavas produce several interesting features in connection with their escape. They expand in the lava of a flow and thus cause the

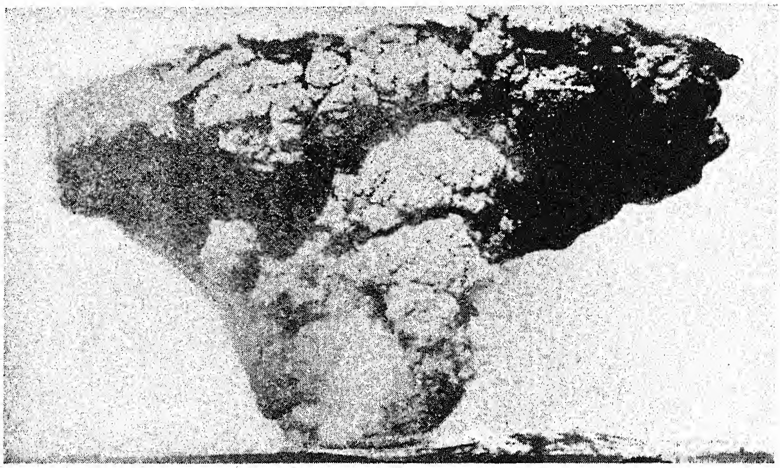


FIG. 34.—Enormous cloud (about four miles high) hanging over Mt. Lassen, California, during the eruption of May 22, 1915. Picture taken at Anderson, California, 50 miles away. (*Photograph furnished by B. F. Loomis.*)

formation of *scoriaceous and pumiceous* rocks; by their explosion they blow the hardened lava above them in the conduit into bits and thus produce *pyroclastic material;* they form clouds above volcanoes, the rain from which assists in the production of *mud flows;* and, finally, when the volcano has become inactive they escape, aiding in the formation of *fumaroles, geysers,* and lastly *hot springs.*

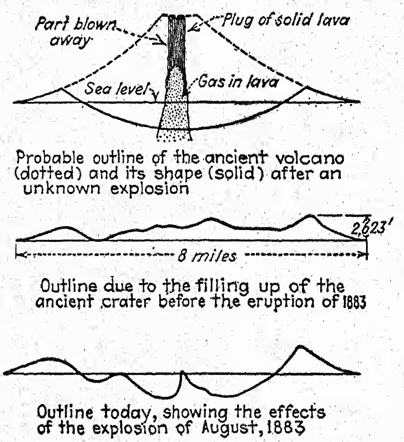


FIG. 35.—Sketches illustrating probable history of Krakatoa, a volcano in the East Indies. (*Figures from "The Eruption of Krakatoa," The Royal Society, London, pp.* 7–23, 1888.)

Scoriaceous rocks (Fig. 36) are extremely porous. They were formed by the expansion of the steam and other gases beneath the hardened crust of a lava. The final escape of the gases from the hardening lava left large, rounded holes in the rock.

Pumice is a rock also formed by the expansion and escape of gases (Fig. 37). In it, many of the holes are in the form of long minute closed tubes, which make the rock so light that it will float on water. These tubes were

formed by the expansive force of large amounts of gases in an extremely viscous lava which cooled very rapidly, forming a glassy rock. Pumice is the rock that is usually formed from the lava ejected from explosive volcanoes. It has been blown miles by explosions. Pine forests in the vicinity of Crater Lake Mountain in Oregon are growing over beds of volcanic dust and pumice that are still powdery beneath the thin layer of soil that has formed over them.

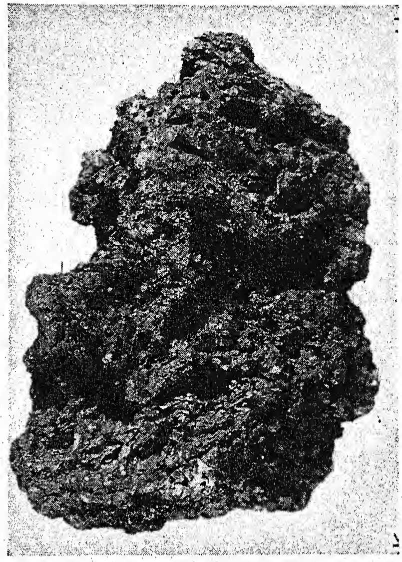


FIG. 36.—Scoriaceous lava (basalt) from Craters of the Moon National Monument, Idaho. The flattened, crooked holes indicate that the lava moved after cavities had been formed by expansion of gases. About one-fourth natural size.

Explosive volcanoes eject great quantities of broken and pulverized lava (*pyroclastic material*). These fragments range in size from great *blocks* weighing tons down to the finest *dust*. Two of these products of intermediate sizes that have special names may be noted. Particles like coarse gravel are called *lapilli*, and more or less rounded masses that are liquid when thrown into the air but cooled before falling to the surface are called *bombs* (Fig. 38).

The steam accompanying an eruption forms clouds from which rain may fall. If much volcanic dust has been ejected, the rain and dust cause great *mud flows* that rush down the sides of the volcano, burying all before them.

Long after the eruption of a volcano has ceased, the escape of gas, steam, and hot water gives evidence of the former activity. The gases and steam may be escaping from hot lava that is still cooling below the surface, or they may be produced when surface water, having percolated downward, comes in contact with hot lava or even solid hot rock. The gases and steam that find their way to the surface through cracks and fissures in the rocks are known as *fumaroles*. The vast number of these fumaroles in a valley near the Alaskan volcano Katmai has given it its name, the Valley of Ten Thousand Smokes (Fig. 39). Vegetation is destroyed by fumaroles, as on Roaring Mountain (Fig. 40), Yellowstone National Park. This area of fumaroles is increasing in size.

A *geyser* (Fig. 41) ejects both steam and hot water and thus represents an intermediate stage between a fumarole and a hot spring. Geysers originate as follows. Water from the surface in descending along a fissure comes in contact with steam rising from some hot rock (solid or

liquid) below and is heated. The pressure of the accumulating steam finally becomes great enough to eject violently the water above it in the

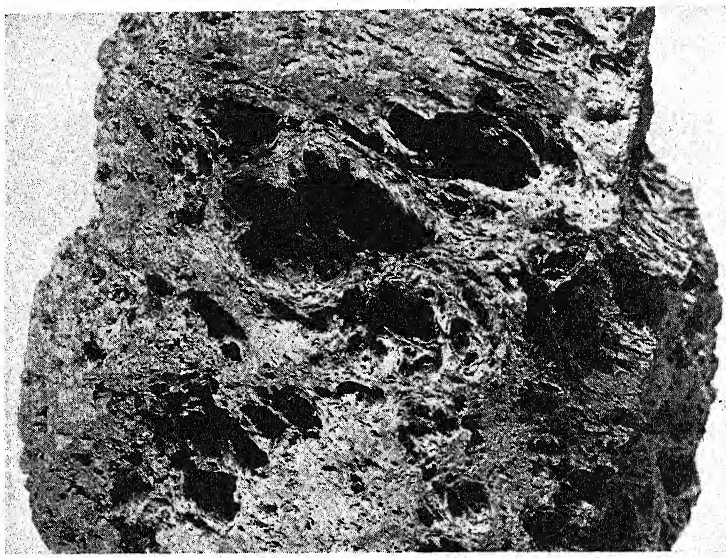


FIG. 37.—Pumice from a bed of volcanic ash and pumice, near Crater Lake, Oregon. Note large holes and thread-like fibers of glass. About one-half natural size.

fissure. The eruption lasts until the pressure is relieved. Water then finds its way back into the fissure and the process is repeated, commonly

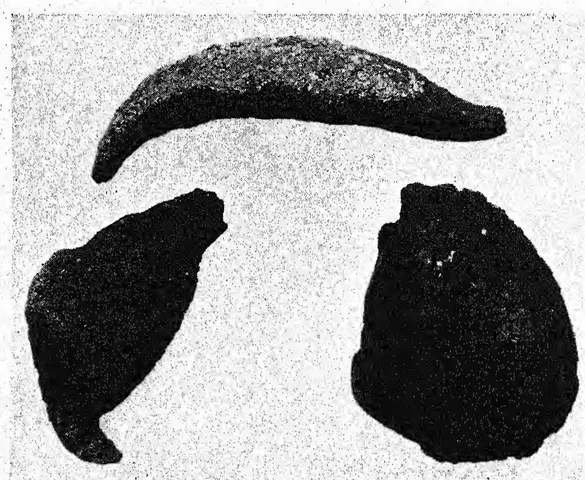


FIG. 38.—Volcanic bombs. One-fourth natural size.

at regular intervals. Thus the action of a geyser is dependent upon surface water from above and steam from a magma below. The magma or rock furnishing the steam is gradually cooling, of course, so the time

interval between eruptions becomes longer and longer. Old Faithful Geyser in Yellowstone Park formerly had an interval of 60 minutes; at present it is 63 minutes.

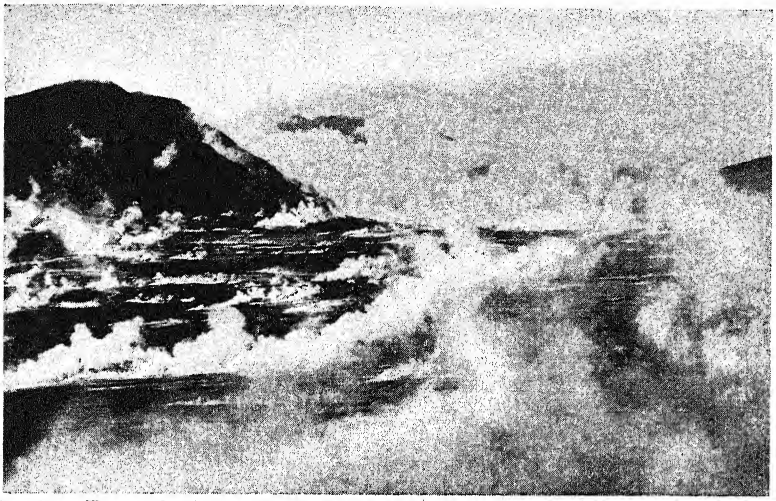


FIG. 39.—Fumaroles in the main arm of the Valley of Ten Thousand Smokes, Katmai, Alaska. (*Copyright by National Geographic Society. Reproduced by special permission from the National Geographic Magazine.*)

FIG. 40.—Roaring Mountain, Yellowstone National Park. Escaping steam and other gases have killed off all the trees. The fumaroles first developed in 1902, in an area 30 feet square near the top of the mountain. (*Photograph taken in* 1928 *by W. A. Tarr.*)

Only three areas, Yellowstone National Park, Iceland, and New Zealand, have the conditions needed to produce geysers. Some of the New Zealand geysers throw water and steam to a height of 1,500 feet, which is the greatest height attained by geysers anywhere in the world.

Finally, when the quantities of steam coming from the lava are no longer sufficient to cause eruptions, water from their condensation,

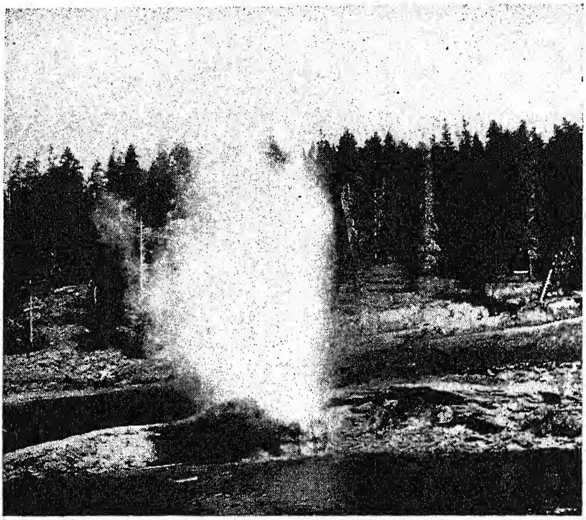


FIG. 41.—Riverside Geyser, Yellowstone National Park. (*Photograph by W. A. Tarr.*)

together with the heated surface waters, will be present as *hot springs.* Eventually even the springs cool down, signifying that the igneous activity is over, at least temporarily.

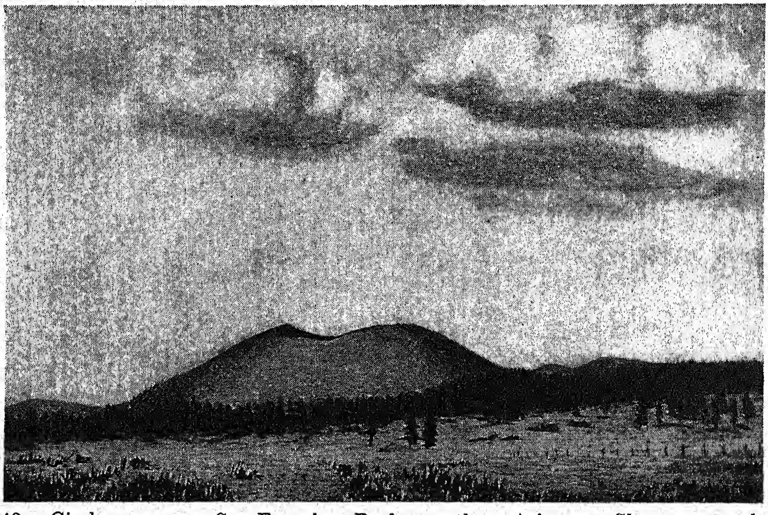


FIG. 42.—Cinder cone near San Francisco Peaks, northern Arizona. Shows crater depression in top. (*Photograph by W. A. Tarr.*)

Cones and Other Features of Volcanoes.—A beautiful symmetry is exhibited by most volcanic cones, the classic example of which is the

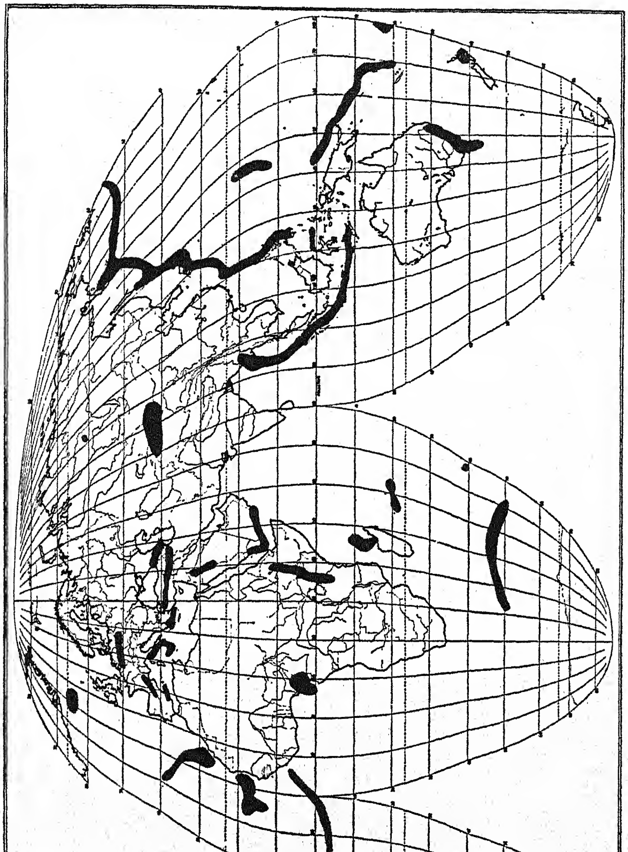


FIG. 43.—Map showing the distribution of volcanic areas in the world. (*Map used by permission of University of Chicago Press.*)

Fuji in Japan. The symmetry of some cones is broken, however, by the presence of small *parasitic cones* upon the sides of the major peak (see Fig. 31). These small cones are formed where volcanic action took place on the sides of the large cone and produced miniature eruptions. A type of cone built most commonly during the closing stages of an eruption (either fissure or volcanic) is a *cinder cone* (Fig. 42), as the final gases in escaping break up the lava which had solidified and blow it out of the crater. Cinder cones are composed largely of lapilli with more or less fine and coarse fragmental material. These cones are usually very symmetrical and have perfectly circular craters. Cinder cones

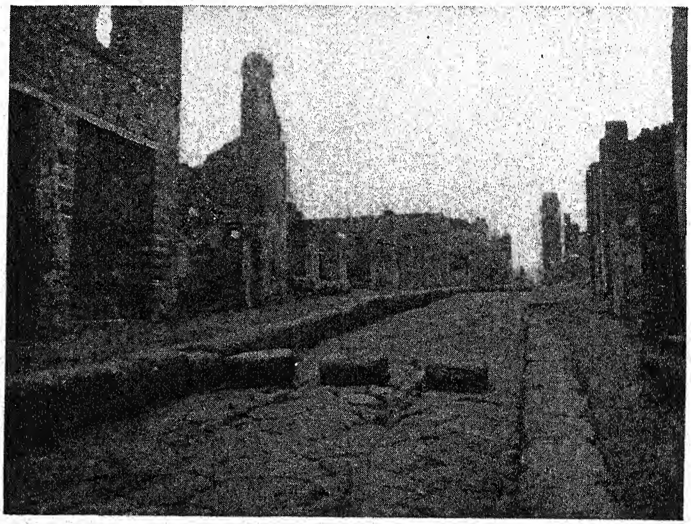


FIG. 44.—Paved street in Pompeii, Italy, after excavation. Note stepping stones and tracks worn by Roman carts. (*Photograph by W. A. Tarr.*)

are very abundant near Flagstaff, Arizona; Lassen Peak, California; and in the volcanic regions of Oregon and Idaho.

Lava caves occur in volcanic lavas, also, and the surfaces of volcanic lavas show the same *smooth, ropy* (see Fig. 27), and *clinkery structures* as do the surfaces of the lava from fissure eruptions.

Location of Volcanoes.—Volcanoes are widely distributed over the earth (Fig. 43) but they are more abundant in certain belts. One such belt encircles the Pacific Ocean and includes many of the islands in it. Other volcanic areas are the islands of the West Indies, those off the west coast of Africa, the Mediterranean region, and Iceland. Most volcanoes occur around or near the margins of the continents, so these areas are regarded as weak zones in the earth's crust where lavas can readily work their way upward. There are more than 400 active volcanoes at present (1934) and many more inactive ones. Very probably numerous submarine volcanoes exist, also, of which we have no knowledge. Of the many known volcanoes we shall describe a few briefly.

Vesuvius.—The very famous volcano Vesuvius had been dormant for an unknown period of time when in A.D. 79, it suddenly became very active. Its eruption consisted of a series of great explosions by which enormous quantities of rock were pulverized and blown high into the air, obscuring the light of the sun. The fragments fell as dust and mud, burying cities and towns. Pompeii, a city of 20,000, located on the shore of the Bay of Naples at the foot of Vesuvius, was buried under 25 or 30 feet of volcanic dust. This city is now being excavated (Figs. 44 and 45) and thus many incidents of the eruption are coming to light. Although most of the inhabitants of Pompeii escaped, we know that some were suddenly overwhelmed and killed by hot gases, for they are found

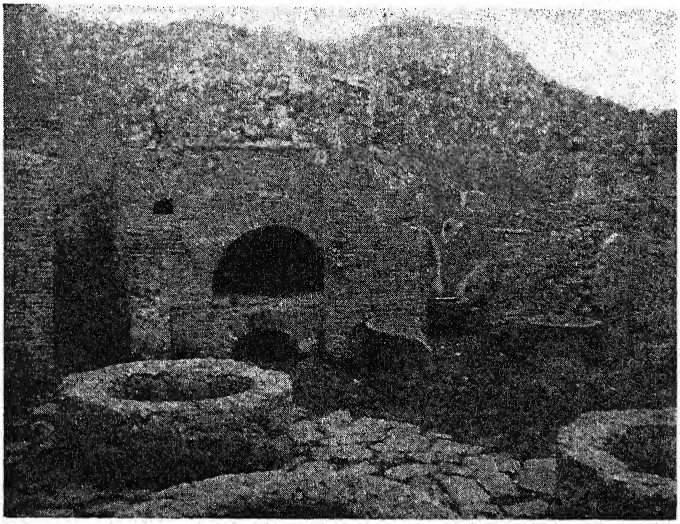


FIG. 45.—Interior of bakery in Pompeii, Italy, showing oven and stone mills (at right) for grinding grain. (*Photograph by W. A. Tarr.*)

in positions that show what they were doing at the time of the explosion. Facial expressions of the plaster casts made of bodies found standing, sitting, and lying down show that death in many cases must have been instantaneous. Foods were found in cooking vessels on stoves and in dishes on tables, people were found sitting about the tables, and thus many facts relating to the people and their habits have been learned. About 2,000 people perished in Pompeii and an unknown number in Herculaneum which is also being excavated. As Herculaneum was buried under 50 feet or more of mud, the work of excavation has not progressed so far as at Pompeii.

Since this first eruption of which we have knowledge Vesuvius has had several dormant periods followed by eruptions, of which some have been violent, destroying many lives. The last great eruption, in 1906, although not so destructive of life as some of the earlier ones, destroyed

much property. Figure 46 illustrates the character of activity prevalent in recent years.

Krakatoa.—Krakatoa, a volcano of the East Indies, is of interest because of the violence of the explosion that destroyed the cone. This eruption occurred on August 27, 1883, and was probably the greatest volcanic eruption of historical times. The steam in the volcano had accumulated in enormous amounts, and after some minor explosions and earthquakes it suddenly blew away the upper two-thirds of the mountain which comprised the island (see Fig. 35). Krakatoa was 2,623 feet high,

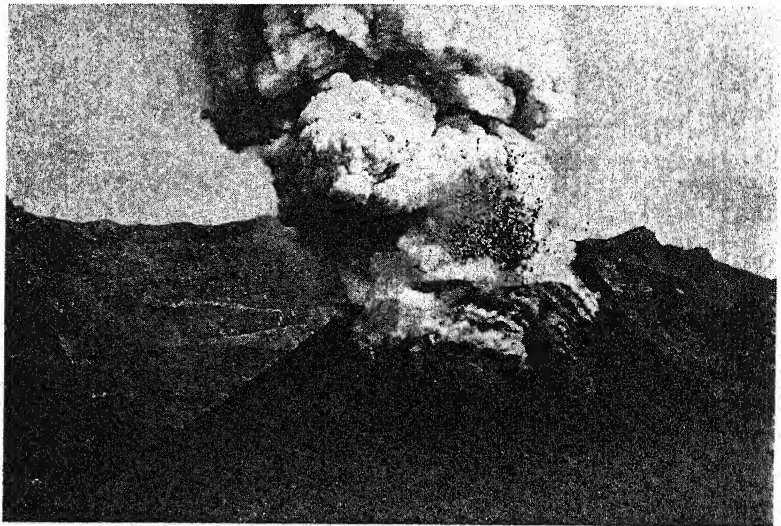


Fig. 46.—Clouds of steam issuing from inner cone in crater of Vesuvius, and numerous fumaroles a little farther down the cone. Black spots in cloud are blobs of lava being ejected. (*From the Illustrated London News, June* 22, 1929.)

but after the explosion the ocean was 1,000 feet deep over most of the area. Only small parts of the outer edges of the cone now remain as islands. The explosion was heard in southern Australia, 2,200 miles away, and at other points at distances of about 3,000 miles. The air waves produced by the concussion traveled around the globe several times. Dust from the explosion was shot to a height of 20 miles or more, and in 15 days was carried around the world by the upper currents of air. Pieces of rock were spread over the ocean floor for miles around. For months afterward the sunrises and sunsets all over the world were of exceptionally brilliant colors due to the dust particles in the air, some of which are estimated to have reached a height of 70 miles. These particles finally settled down over all parts of the earth. A great sea wave which was created by the explosion rushed upon neighboring shores, destroying hundreds of towns and about 30,000 people. Had this eruption occurred in a densely populated part of the earth, the loss of life would have been

tremendous. Since this eruption Krakatoa has been fairly quiet, only occasionally showing signs of activity.

Mt. Pelée.—Mt. Pelée, on the island of Martinique in the West Indies, was also an explosive volcano, but its last eruption was of a different type. The city of St. Pierre, located on a flat plain on the sea shore, lay at the foot of the volcano. Pelée became active late in April, 1902. Explosions of gases and dust accompanied by earthquake shocks were the first evidence of what was to come. It is worth noting that the gases ejected during these preliminary explosions were so poisonous that horses in the streets of St. Pierre were killed. The explosions steadily increased

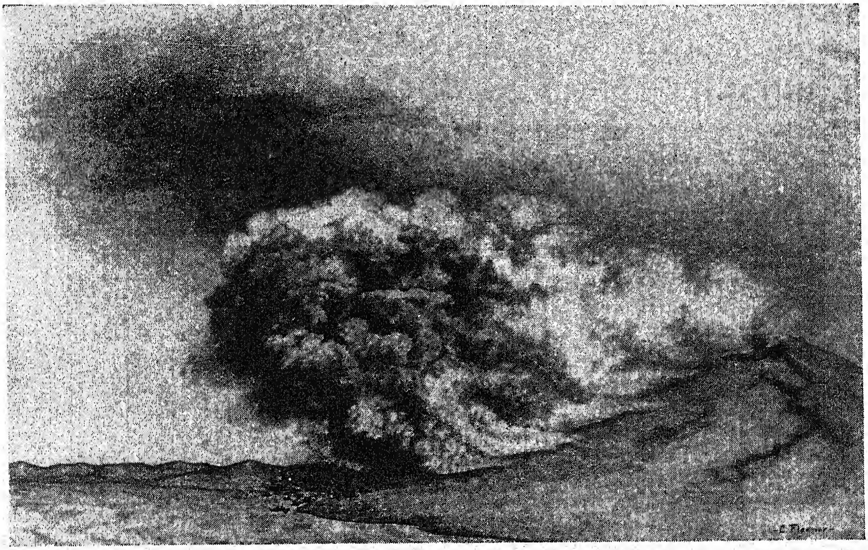


Fig. 47.—Cloud of poisonous gases from Mt. Pelée rolling down on the city of St. Pierre, Martinique.

in violence until on May 8 a terrific eruption of dust and hot poisonous gases occurred. This great cloud of dust and gas swept out of the crater through a notch in its south side and rolled down the cone and across the plain to St. Pierre and its harbor (Fig 47). It traveled with such tremendous force that in two minutes it had destroyed all in its path: buildings, people, trees, even the boats in the harbor. Fire finished the destruction of the city and then rain from the condensed steam carried the dust down as mud and buried it. Very few of the 30,000 inhabitants escaped; one survivor, a prisoner in a dungeon, was found many days later. As the activity of the volcano grew less, a great column of lava slowly rose through the crater to a height of 1,200 feet. This column is known as Pelée's Spine (Fig. 48). It has since gradually disintegrated and decreased in height.

Mt. Katmai.—Mt. Katmai is on Alaska Peninsula in southwestern Alaska, about 750 miles due west of Juneau. As it is located in a very

sparsely settled country, we have no record of any action previous to the eruption of 1912. This eruption occurred about 1 P.M. on June 6, and was witnessed only by a few natives. The noise of the explosion was heard at Juneau. The eruption was followed by another at 11 o'clock that night and by a third at 10:40 the next night. During the first explosion an enormous quantity of gray volcanic dust was ejected, which began to fall in Kodiak, 100 miles away (Fig. 49), about 5 o'clock that afternoon. By 6:30 the dust was so thick that the darkness of night prevailed (at that time of the year daylight at Kodiak lasted nearly 24 hours). The fall ceased at 9:10 the next morning (the dust was then 5 inches deep), but ashes from the second explosion began falling at 12:30 P.M. and in an hour and a half it was again dark. The darkness continued until 2:30 P.M. on June 8. Dust from the explosions fell

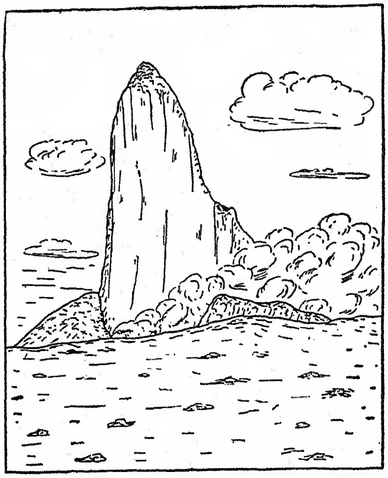


FIG. 48.—Column of lava (called Pelée's Spine) that rose from crater of Mt. Pelée. (*After photograph by E. O. Hovey, Amer. Jour. Sci., vol.* 16, 1903.)

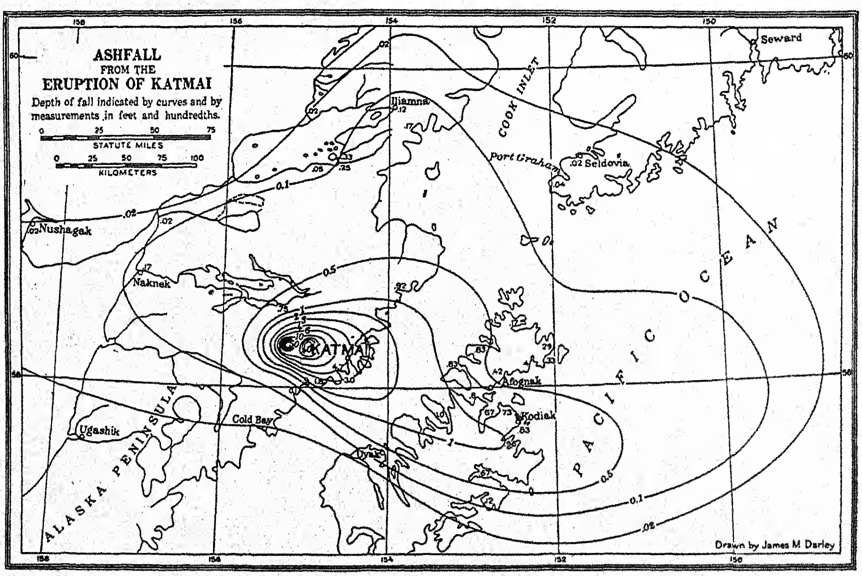


FIG. 49.—Map of the ashfall in vicinity of Katmai, Alaska. (*Copyright by National Geographic Society. Reproduced by special permission from the National Geographic Magazine.*)

1,500 miles from the volcano. The extent of the area covered by 0.02 foot or more of dust is shown in Fig. 49. It is estimated by Griggs that

4.75 cubic miles of dust was blown out of the volcano; that a cubic mile of coarse ash was ejected in the sand flow in the Valley of Ten Thousand Smokes; and in addition that enough material from smaller craters was ejected to bring the total amount to 6.25 cubic miles. It would take all the stone crushers existing at the present time in the United States

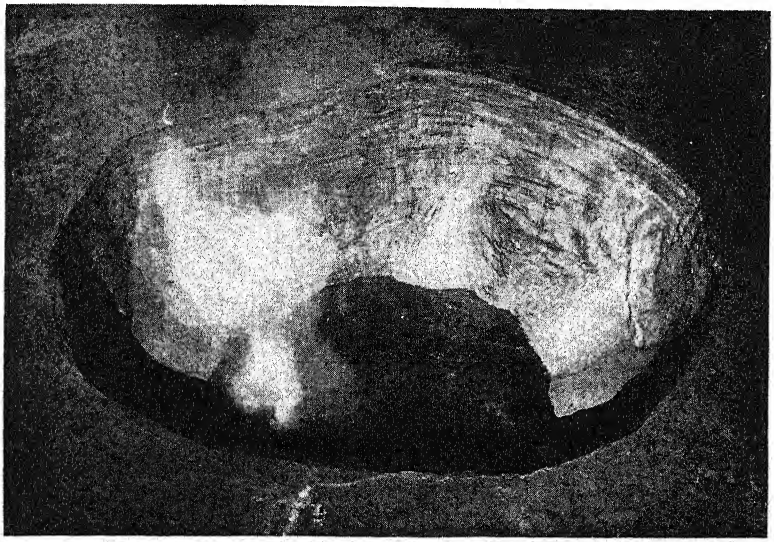


FIG. 50.—Air view of Halemaumau fire pit in crater of Kilauea, Hawaii. Fire pit is 3,000 by 3,400 by 1,400 (depth) feet. Wall of crater in background. (*Courtesy of U. S. Army Air Corps.*)

about 500 years to produce this quantity of crushed material. For six months after the dust was thrown into the air at Katmai a decrease in the amount of heat received from the sun was noticeable throughout the the world. The amount of water ejected as steam was enormous, also. A study of the pumice resulting from the explosion indicates that the

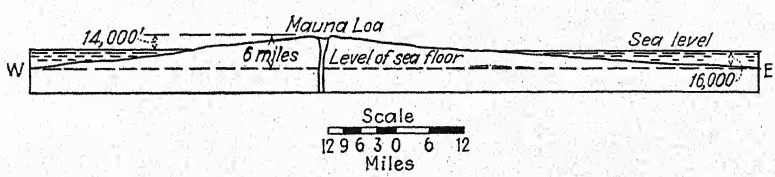
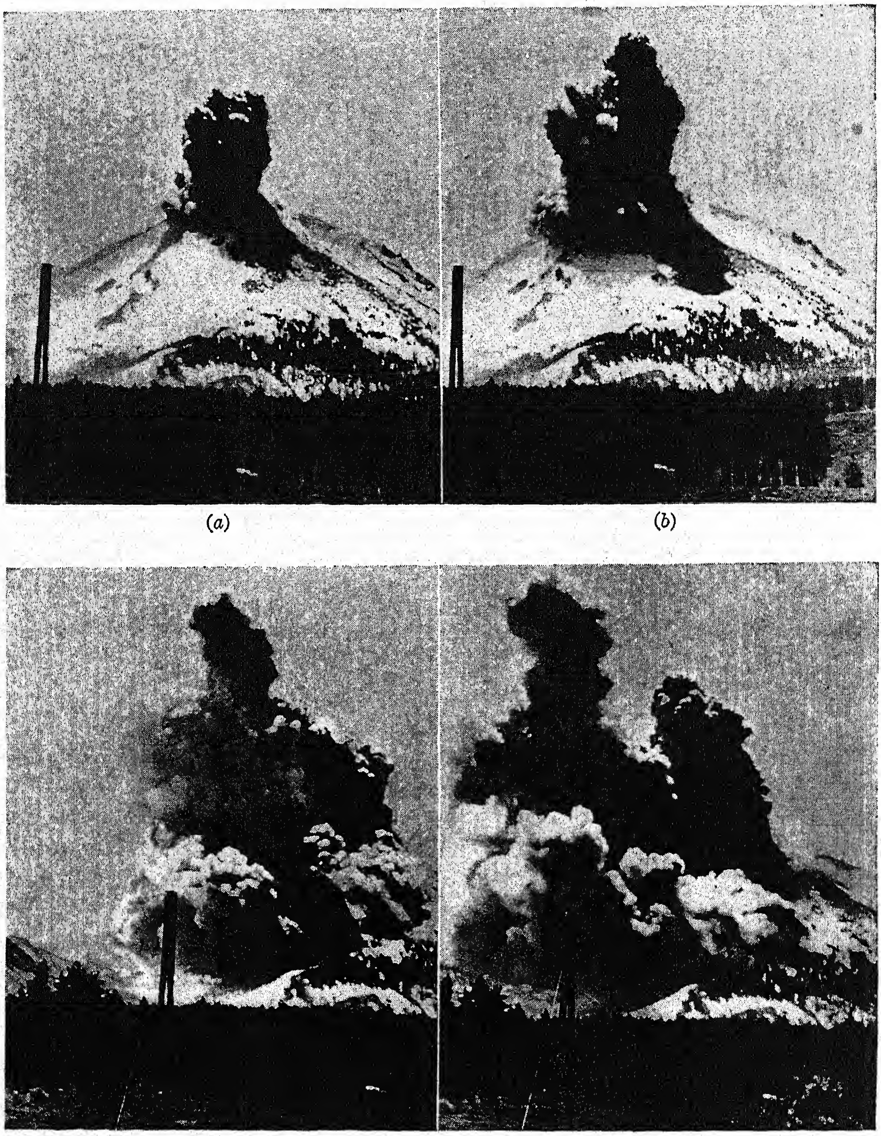


FIG. 51.—Sketch of Mauna Loa volcano, Hawaii, drawn to scale (vertical and horizontal the same) to show its enormous height above the sea floor.

quantity of gas it contained was about 12 times greater than its own volume. This was water newly added to that at the surface of the earth.

The Valley of Ten Thousand Smokes, lying several miles northwest of Katmai, covers about 53 square miles. Before the eruption of Katmai the floor of this valley had been covered (in places to a depth of nearly 100 feet) by a white-hot mass of volcanic sand, which together with much

steam had welled up from below through fissures in the floor of the valley. Though Katmai is now (1934) quiet, in this valley steam is still escaping



(a) (b) (c) (d)

Fig. 52.—Photographs taken at intervals of a few minutes during eruption of Mt. Lassen, June 14, 1914. (*Reproduced by permission of B. F. Loomis, the photographer.*)

from a vast number of fissures (Fig. 39). The temperature of the steam from some of the fumaroles is very high; in one it is 1200°F. Such steam is invisible and a piece of wood placed in it catches fire. During the

expeditions of the National Geographic Society to this region considerable cooking was done over these natural cookstoves.

Hawaiian Volcanoes.—The Hawaiian Islands are entirely volcanic in origin. They contain many volcanoes, all of the quiet type, but only Mauna Loa (nearly 14,000 feet high) and Kilauea (about 4,000 feet high) are widely known. The craters of these volcanoes are large; that of Mauna Loa being 2 by 3 miles in areal extent and 1,000 feet deep; and that of Kilauea, about 3 miles in diameter and over 1,000 feet deep. Within each of these craters are local fire pits (Fig. 50). The lava usually breaks through the sides of these volcanoes and flows quietly down them, and thus the volcanoes have broad, flat cones. The width of their bases, being below the ocean, is unknown; but considering their height and the fact that they are built up from the floor of the ocean, which is 16,000 feet deep around them, they must be enormous peaks (see Fig. 51).

Mt. Lassen.—Mt. Lassen in northern California is the only even moderately active volcano within the territory of the United States proper. The volcano, which is 10,460 feet high, had been dormant for 200 years until 1914 when several mild eruptions occurred (Fig. 52). Two violent eruptions occurred in 1915, one on May 19 and the other on May 22 (see Fig. 34). The early activity was mainly explosive action, which removed much material from the old crater, allowing the rising lava to fill it and overflow slightly. This lava then solidified, forming a solid lid in the crater under which the gases accumulated until finally the lid was lifted and a horizontal explosion took place from under it. Lava flowed down the mountain side, melting the snow and destroying everything in front of it. The water from the snow, mixed with the volcanic dust, caused a great mud flow. Mt. Lassen, which is readily accessible, is quiet now, but there are many fumaroles, hot springs, and boiling mud pots in its vicinity, and many lava caves in the earlier lava flows about the peak.

STRUCTURAL FEATURES OF IGNEOUS ROCKS

The structural features of igneous rocks are rather large features, best seen in the field, though they may be studied also in laboratory specimens. The following structural features are distinctive of igneous rocks, and can be used to distinguish them from the other types of rocks:

Ropy structure.
Clinkery structure.
Block structure.
Flow structure.
Columnar structure.
Massiveness.

Ropy and *clinkery structures* have already been described (page 25).

Block structure is the result of the formation of a crust on a lava flow followed by movement of the still-liquid portion below. The crust is

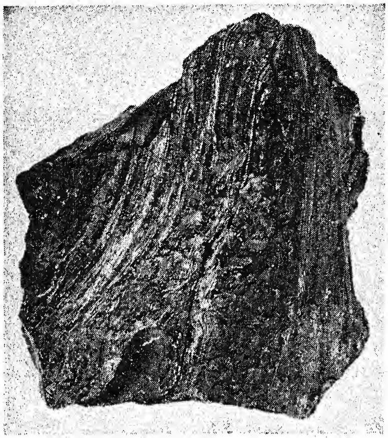


FIG. 53.

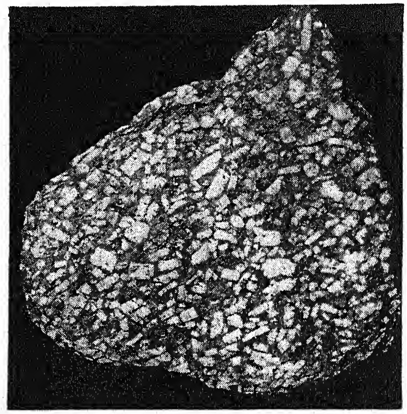


FIG. 54.

FIG. 53.—Flow structure in obsidian.

FIG. 54.—Flow structure due to rudely parallel arrangement of phenocrysts. This arrangement was caused by movement of viscous lava.

thus broken into blocks and becomes a rough jumbled mass as the lava moves forward.

FIG. 55.—Columnar structure in basalt, Giant's Causeway, Ireland. Hammer is 12 inches long. Some columns are concave on ends (those containing rain water), others convex. (*Photograph by W. A. Tarr.*)

Flow structure is the result of movement in a viscous lava. It is seen as lines or streaks of different color in a rock (Fig. 53), or as the parallel arrangement of the phenocrysts of a porphyry (Fig. 54). This banding

is well illustrated by the lines and bands formed in taffy as it is being pulled. Thick asphalt shows the same features, also.

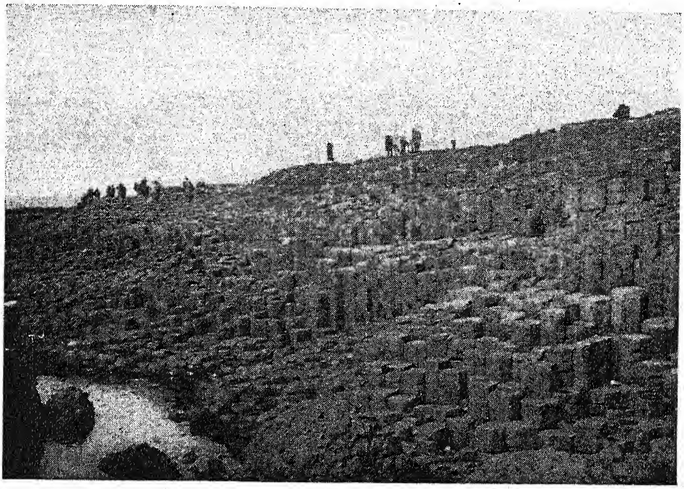


FIG. 56.—The Giant's Causeway, Ireland. Note great number of columns—estimated at 70,000. (*Photograph by W. A. Tarr.*)

Columnar structure results from a certain type of jointing formed in igneous rocks as the lava cools and contracts. The joints or cracks which start on the surface of the cooling mass (a flow, dike, or sill) penetrate deeper and deeper as the interior cools and contracts. The cracks are remarkably uniform in their spacing, the result being extraordinarily symmetrical columns (Figs. 55 and 56). An interesting feature of these columns is their dominantly six-sided character, although the number of sides ranges from three to nine. The columns of the Giant's Causeway on the north coast of Ireland are among the most perfect known (Fig. 57). In the main part of the Causeway the columns average about 15 inches in diameter, in other parts several feet. The columns in the Devils Tower in Wyoming are from 6 to 8 feet in diameter (see Fig. 20, page 21).

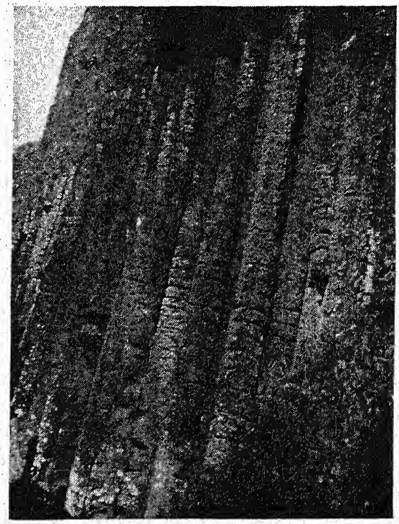


FIG. 57.—The Giant's Organ, a group of remarkably perfect columns in the Giant's Causeway, Ireland. (*Photograph by W. A. Tarr.*)

Massiveness is a term applied to igneous rocks that, over a wide extent, are uniform in texture. This feature is most typical of granites,

diorites, and similar rocks, and is but rarely exhibited by other types of rocks.

THE COMMON MINERALS OF IGNEOUS ROCKS

One of the outstanding facts about igneous rocks is that the great majority are aggregates of only four minerals. Many other minerals occur in igneous rocks but either they are minor constituents or if fairly abundant they give rise to rare types of rocks that are of interest chiefly to the petrographer. We shall ignore these rarer varieties in our study, aiming only to acquire a working acquaintance with the simpler rocks.

The four minerals that form the basis of the igneous rocks are, in the order of their abundance: *feldspar*, *quartz*, *hornblende*, and *pyroxene*. Leith and Mead have given the following estimate as to the relative abundance of the minerals found in igneous rocks:

Minerals of Igneous Rocks	Percentage
Feldspars	50.0
Quartz	20.5
Hornblende, pyroxene, and olivine	17.0
Mica	7.5
All other minerals	5.0
Total	100.0

The description of the minerals, which follows, gives necessarily only their general characteristics; the student must study them in the laboratory, also, and if possible, in the field.

The Feldspars.—The feldspars are minerals containing potassium, sodium, calcium, aluminum, and silica. A very convenient way of

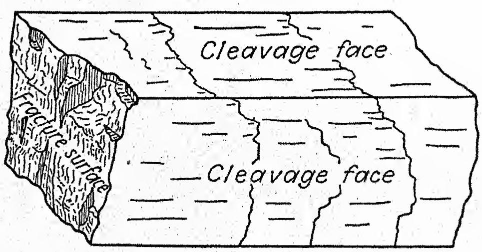


FIG. 58.—Sketch of cleavage fragment of orthoclase, showing the two smooth cleavage faces at right angles to each other, and the position of the fracture face.

stating their composition is to say that they are silicates of potassium, sodium, calcium, and aluminum. There are two common feldspars: orthoclase, which contains potassium; and plagioclase, which contains sodium and calcium. The feldspars are white, pink, red, gray, and, rarely, dark gray or black. They are so hard that a fragment rubbed on glass will scratch it. Feldspars have two smooth cleavage surfaces, *i.e.*, they break readily along two surfaces. These two surfaces are at

right angles (or nearly so) to each other (Fig. 58), and the break in the third direction is rough and jagged. Practically all common igneous rocks contain at least a little feldspar. The term *felsic* ("fel" for feldspar; "s" for silica or quartz; and "ic," the general ending) is coming into common use for these minerals.

Quartz.—Quartz is common not only in igneous but in all kinds of rocks. It is composed of silica (SiO_2), and is the hardest of the common minerals found in rocks. Its hardness is generally given as 7 in a scale that runs from 1 to 10. (The diamond has a hardness of 10, being the hardest substance known.) Quartz occurs in all colors; but transparent, white, pink, red, violet, and green quartz are the most common varieties. Quartz does not have cleavage, but breaks with an uneven surface that looks like glass. Well-developed crystals of quartz are common. The crystals are six-sided and on the ends have faces arranged as six-sided pyramids. Most sand consists dominantly of quartz grains.

Hornblende and Pyroxene.—Hornblende and pyroxene are similar in composition. Both are iron-magnesium-calcium-aluminum silicates; but, due to variations in the constituent amounts of these elements, the two minerals possess different physical properties. Numerous varieties of each mineral occur. Both minerals are black or dark green and have a hardness of 5 to 7. Both have two cleavages, and their different cleavage angles (for hornblende 124 and 56°; for pyroxene 93 and 87°) are the most important physical means of distinguishing between them. Hornblende crystals may be longer and more slender than those of pyroxene. The occurrence of the two minerals as small grains in igneous rocks makes it impossible, even by their cleavage angles, to distinguish between them. These two minerals are commonly called the *ferromagnesian* ("ferro" means iron) minerals, or the newer term *mafic* ("ma" for magnesium; "f" for iron; "ic," the general ending) minerals. Rocks rich in hornblende or pyroxene are called *ferromagnesian* or *mafic* rocks. In a great many dark-colored rocks the beginning student will find it impossible to distinguish between these two minerals and would better simply call the rocks "mafic rocks."

The Micas.—There are two varieties of mica; one is white or transparent, *muscovite;* the other is black, *biotite.* Micas are easily determined because they have shiny cleavage faces and split readily in one direction into extremely thin sheets. Both biotite and muscovite are fairly common.

Olivine.—A mineral of somewhat rarer occurrence in igneous rocks is *olivine.* It is an iron-magnesium silicate. It occurs in certain dark mafic rocks, notably one called *peridotite* which, though not very abundant at the surface, is believed to be the dominant rock below the gabbroid zone. Olivine has a characteristic olive-green color, breaks unevenly, and has a glassy luster.

NAMING THE IGNEOUS ROCKS

Having followed the development of igneous rocks from their source in the magma deep within the earth's body to the various forms of the solid rock, we now come to the final phase of their consideration, *i.e.*, the development of names by which we may know them. There are many different kinds of igneous rocks; hundreds, in fact. Fortunately, however, for the beginning student and layman, geologists have found it possible and convenient to group most igneous rocks under a few simple names, called *field names* because they can be applied to a rock in the field before it has been critically studied in the laboratory. These are the names that should be used by the beginning student of geology.

Three factors are involved in developing the names of the different igneous rocks: the *texture* (always important), *color*, and the *mineral composition* (if it can be determined).

Texture is the chief feature used in developing the names or classes of igneous rocks, as all of them can be placed in one of four textural groups, which are as follows:

Texture	Characteristics
Grained	Mineral grains recognizable; larger than granulated sugar.
Dense	Mineral grains indiscernible; the rock has a stony appearance.
Glassy	Rock is like glass.
Fragmental	Composed of fragments of minerals and rocks.

Further subdivision of these groups will be necessary, as any rock of the first three groups may occur as an even-grained rock or as a *porphyry*.

The four textural groups of rocks we shall subdivide on a basis of *color*. For our purpose, only a division into "dark-colored" and "light-colored" rocks will be needed. As dark colored, we shall designate black, dark gray, and dark green rocks; as light colored, those that are light gray, light green, white, red, pink, brown, and yellow.

The third and last factor we must consider in naming the igneous rocks is their *mineral composition*. Inasmuch as it is only in the grained rocks that all the mineral grains are large enough to be determinable, it is only in naming the rocks of that group that we can make use of the mineral composition. Even in the fine-grained varieties of the grained rocks it may be difficult or impossible to determine all the constituent minerals.

Combining now the different kinds of texture, varieties of color, and known mineral composition, we are able to produce the following table for determining igneous rock names.

IGNEOUS ROCK TABLE

		Light colored		Dark colored
		Felsic minerals predominate		Mafic minerals predominate. Some feldspar
		Feldspar and quartz	Feldspar and some mafic minerals	
Grained	Even-grained	Granite	Diorite	Gabbro
Grained	Porphyritic	Granite porphyry	Diorite porphyry	Gabbro porphyry (rare)
Dense	Even-textured	Felsite		Basalt
Dense	Porphyritic	Felsite porphyry		Basalt porphyry
Glassy	Even-textured	Pumice, Obsidian		
Glassy	Porphyritic	Obsidian porphyry		
Frag-mental		Tuff, Volcanic ash, Volcanic breccia		

A sample determination will illustrate the ease with which the name of an igneous rock may be determined by the use of this table. Suppose the specimen of rock is light colored; it is assigned to the left-hand section of the table. Closer inspection shows that the mineral grains of the rock are recognizable, hence it comes under the section of the grained rocks. The determination of the minerals in the specimen shows that it consists dominantly of feldspar and quartz, and so we decide that the name of the rock is "granite." By a similar use of the table the name of any common igneous rock can be determined.

As seen by the table, grained, dense, or glassy rocks may be porphyritic, but porphyries are most common in dense rocks. Care should be used in determining a porphyry. The groundmass must comprise more than 50 per cent of a rock in order to designate the rock a porphyry. The name of the phenocrysts may be used as a part of the rock name; thus, if the phenocrysts in a felsite are quartz, the rock may be called a "quartz-felsite porphyry"; or, as is commonly done, the term "felsite" may be dropped and the rock called a "quartz porphyry." If two kinds of phenocrysts are present, as quartz and feldspar, the name of the rock would be (if quartz were the smaller in amount) "quartz-feldspar porphyry." The phenocrysts of porphyries may be any of the minerals that occur in igneous rocks.

Tuff is a name used for accumulations of volcanic dust; and *volcanic breccia* ("breccia" means "broken") is the name for volcanic deposits of larger angular fragments.

MODE OF OCCURRENCE OF THE DIFFERENT KINDS OF IGNEOUS ROCKS

There is more or less of an association between the type of igneous rock and its mode of occurrence, as would be expected when it is recalled that the texture of the rock is dependent upon the rate of cooling of the parent mass.

The Grained Rocks.—The grained rocks resulted, of course, from magmas that cooled under conditions favoring the growth of large grains. For the most part these rocks were formed at considerable depths below the surface. They are the dominant rocks in batholiths, laccoliths, and large sills and dikes. All of the grained rocks are found at the surface, owing to erosion, but granites are by far the most abundant there, as the name "granitic" for the outer 10 or 12 miles of the earth's crust indicates (see Fig. 7, page 12). Diorites, though common at the surface, are considerably less abundant than the granites. The gabbroid rocks are fairly widespread at the surface but become increasingly abundant downward. Below the zone in which they are found is a zone rich in olivine (the peridotitic zone, see Fig. 7). The grained rocks are not commonly porphyritic. Some granites and diorites are porphyritic, however, especially those occurring in dikes and sills; but the magmas which gave rise to the mafic rocks were so fluid even at low temperatures that these rocks are usually wholly crystalline. Cooling and crystal growth may occur in two stages, however; hence even gabbro porphyries are known.

The Dense Rocks.—The dense rocks occur commonly in lava flows. The silica content of the felsites is about the same as that of the granites and diorites; in fact, had the lava forming the felsites cooled slowly, it would have become granite or diorite. As this felsite lava was usually viscous, it could not flow far from the opening but solidified rapidly, hence felsites are common in volcanic lava flows. Basalts were formed from magnesium-iron-rich lavas that, being quite fluid, were able to flow for long distances. In the vast area of lava flows of northwestern United States the rock is dominantly basalt. In addition to these extrusive occurrences both felsites and basalts occur as dikes, sills, and necks. The dense rocks are very commonly porphyritic because most lavas that finally reach the surface are halted for a time on their way up. During this time various minerals start to crystallize, and these crystals are the phenocrysts of the rock that is formed after further movement toward the surface has taken place.

The Glassy Rocks.—The glassy rocks are always formed at the earth's surface, where the lava cools very rapidly. As they are formed

from lavas rich in silica, they, like the felsites, would have been granite or diorite had the lava cooled far below the surface. Such silica-rich (felsic) lavas are very viscous at the surface, and it is the expansion of gases in them that gives rise to pumice. Obsidian Cliff in Yellowstone Park is a good example of a thick mass of glassy rock. Basaltic lavas rarely form glassy rocks because, on account of their extreme fluidity, crystals can grow in them rapidly. Rarely, a thin layer of black glass is formed around the outside of a mass of solidifying basaltic lava. The formation of porphyries is possible in glassy rocks but it is not common.

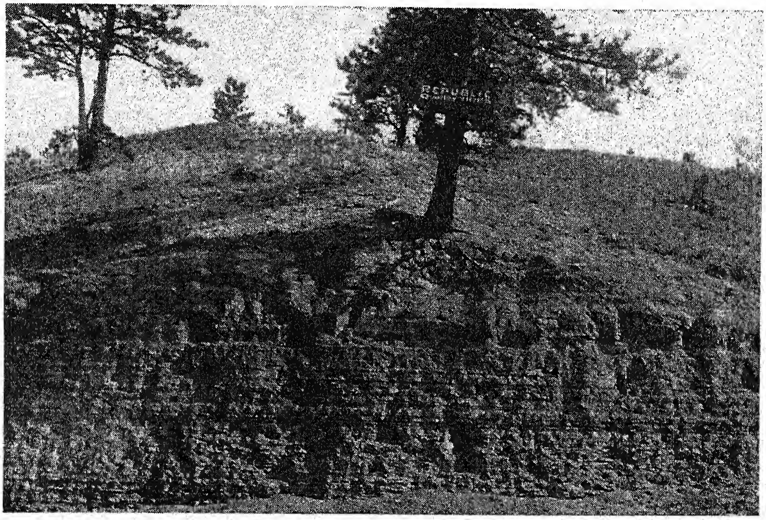


Fig. 59.—Tuff beds containing fossil plants and animals, near Florissant, Colorado. (*Photograph by W. A. Tarr.*)

The Fragmental Rocks.—The fragmental rocks are formed from the material ejected from the explosive type of volcano. The coarse fragments and lapilli, which form the volcanic breccia, settle near the volcano, but the volcanic dust and pumice may be carried long distances by the wind. Dust from volcanoes that formerly were active in the Rocky Mountains is now found as tuff beds as far east as central Kansas and Nebraska. Beds of tuff thousands of feet in thickness occur in the San Juan Mountains in southwestern Colorado. Volcanic dust becomes somewhat stratified, as dust particles of the same size settle together to the earth. In this respect, tuffs resemble sedimentary rocks. Tuffs have been found that were deposited in water (Fig. 59) and contained fossils of various kinds. Much care is required in the determination of such deposits, for it is readily seen that the presence of fossils in a rock is not sufficient evidence to prove that a rock is wholly of sedimentary origin.

ORE DEPOSITS RESULTING FROM IGNEOUS ACTIVITY

Having discussed the formation of igneous rocks from magmas, it will be of interest to note also the formation, from these same magmas, of deposits of the valuable metals and minerals used by man. Such deposits are called *ore deposits* or *mineral deposits*. Thus, we read of a "gold ore" or a "platinum ore." Some magmas contained, in addition to the elements that went into the formation of the igneous rocks, small amounts of various rare metals or other elements, which under the proper conditions were concentrated into deposits sufficiently valuable to pay man to go to the expense of mining them. It was only the occasional magma, however, that contained such elements; and, even then, only occasionally that a concentration of those elements into an ore deposit took place. This is shown by the fact that platinum, or nickel, or diamonds, for example, have been found in only a very few localities over the entire earth. The earth is thus shown to be heterogeneous in composition. We shall consider briefly the separation, in the magma, of these valuable substances from the igneous rocks, and the forms they assumed upon being deposited.

We have already seen that, as a magma cooled and the igneous rocks solidified from it, the gases (largely steam) were eliminated. It is in these gaseous, and later liquid, solutions (*magmatic solutions*) forced out of the solidifying rock that the valuable elements were contained. The gaseous solutions are called *mineralizers*, for a double reason: (1) because they aid in keeping a lava in a liquid state and thus allow minerals to grow to large sizes, and (2) because they are very strong solvents, dissolving the most insoluble of elements (such as gold and lead), which are subsequently deposited as minerals. This solvent action of the solutions is due to the contained gases, *viz.*, steam, carbon dioxide, chlorine, sulfur, and, more rarely, stronger gases such as fluorine and boron.

It should be noted that the majority of ore deposits are connected with large igneous masses, such as batholiths and, less commonly, thick dikes, sills, and laccoliths. As these large masses cooled, the rock-forming minerals solidified and the gaseous solutions were thus forcibly eliminated. A small part of them passed outward into the surrounding rocks during the early stages of cooling; but, as soon as the outer part of the igneous mass was solid (the outer part, of course, cooled first), the gases were steadily forced inward as the solidification progressed and thus accumulated in the still-liquid interior of the cooling mass (Fig. 60-A). These gaseous solutions, having penetrated all parts of the magma, had acquired by their powerful solvent action whatever rare elements or metals (if any) the magma contained. Some of the magmas were rich in one or two metals, such as gold, gold and silver, copper, iron, lead and zinc, or a rarer metal. Some magmas were rich in several metals:

commonly, such an association as copper, iron, lead, zinc, gold, and silver.

After the magma had become solid, it contracted with continued cooling, and thus cracks and fissures were developed in the solid outer part (Fig. 60-B). The magmatic solutions on the interior were under great pressure (largely due to the expansive force of the gases), and therefore they took advantage of these openings formed and passed outward into them (Fig. 60-B). They were able to force their way into

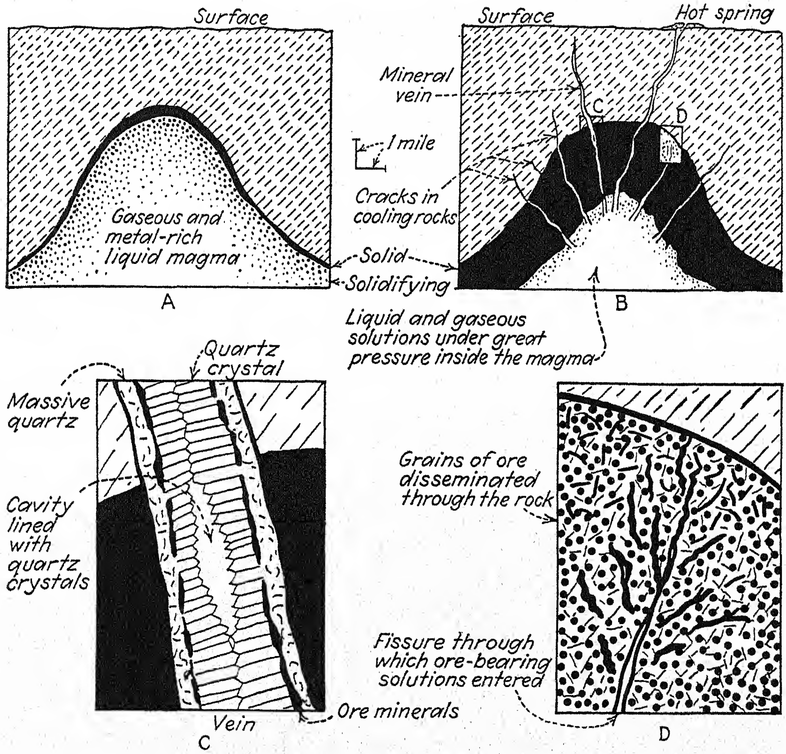


FIG. 60.—Sketch showing the formation of mineral deposits from a magma.

even very tiny fissures and to move outward through them to areas of less pressure, carrying with them, we must remember, the valuable metals and minerals they had collected from the magma.

As time passed, the temperature of the solutions grew less, of course, and especially because they found their way into cooler areas near the surface and probably mingled with the cooler solutions there. As a result many changes took place in the solutions and these changes caused the deposition of the metals and minerals they were carrying (Fig. 60-C). The deposition took place not only near the surface, but also, under favorable conditions, deep within the earth. Erosion later cut away

the overlying rock and exposed some of the deposits at the surface, where man discovered and made use of them.

The deposits made by magmatic solutions are of innumerable forms, the most common of which is a vein-like deposit (Fig. 60-B and C, and Fig. 127, page 128) filling fissures and cracks in the rocks. These *veins* are of all sizes and shapes. Some are many miles long and 100 feet wide; others are no thicker than a sheet of paper. They are found in all kinds of rocks and at all depths. Some mines in which copper and gold veins are being worked are over a mile deep. Another common form of deposit is a *disseminated deposit*, in which the valuable mineral is scattered throughout the rock (Fig. 60-D and Fig. 61). These deposits may be hundreds of feet thick. One at Bingham Canyon, Utah (Fig. 62), is being mined on the surface with steam shovels and the whole side of a mountain has been cut away.

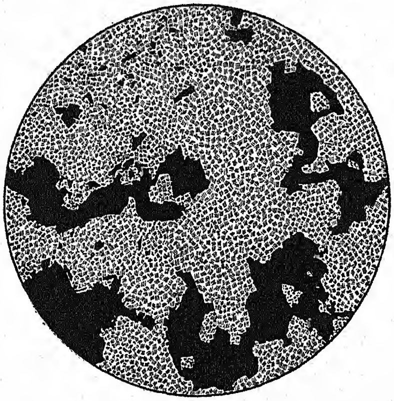


FIG. 61.—Sketch of a disseminated deposit (a black lead mineral in limestone) as seen through a microscope. (*Buckley, Missouri Geol. Sur., vol.* 9, *p.* 213.)

Inasmuch as these deposits whose origin we have been considering are formed directly from cooling magmas, they are called *primary deposits*. They include the world's largest *copper*, *gold*, *silver*, *lead*, *zinc*, and certain, but not all, *iron* deposits. Other valuable but less common metals, like *chromium* (used for plating), *nickel*, *tin*, and *tungsten* (used in electric lights), are also formed by magmatic solutions, and so are likewise primary deposits.

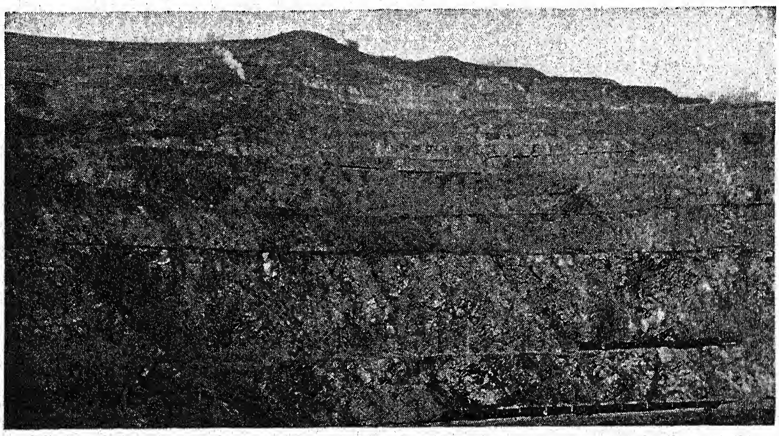


FIG. 62.—Open-cut copper mine, Bingham Canyon, Utah. (*Photograph by W. D. Keller.*)

Since the igneous rocks are the primary rocks, they are the source of all the substances found at the surface of the earth. Not all of the products at the earth's surface are primary, however, as certain valuable deposits there, as well as certain kinds of rocks, were formed by secondary processes. These *secondary deposits* are all found on or near the surface and are the result of the alteration of the igneous rocks, or primary mineral deposits, by water, aided by various agents (as will be discussed in the next chapter). Deposits of the metals *aluminum* and *platinum* are examples of the many valuable mineral deposits due to secondary processes, and *salt* is an example of a useful rock derived by secondary processes.

Most aluminum deposits are the result of the ground water's attacking a feldspar-rich rock, leaching out the potassium, sodium, calcium, and silica, and so leaving the very insoluble aluminum behind to accumulate into a valuable deposit. The largest deposit of aluminum in the United States is just south of Little Rock, Arkansas.

Platinum is a very insoluble, heavy mineral occurring in the original primary rock (usually a rock rich in the mafic minerals) as the metal, but in small grains scattered through the rock (thus a disseminated deposit). As valuable as the metal is, such a deposit could not be mined profitably, but various geologic processes may bring about a concentration of the grains. If the rock containing the platinum is exposed at the surface, it will break down or disintegrate into soil and the grains of platinum will thus be loosened. Streams may wash away the soil and leave the very heavy platinum grains in the stream bed along with sand and gravel. Thus the platinum grains slowly accumulate until a deposit known as a *placer deposit* is formed. It is a very simple matter then to wash away the sand and gravel and obtain the platinum. The world's largest deposit of platinum is in Russia, on the east slope of the Ural Mountains.

The two elements sodium and chlorine composing salt (NaCl) were present in the original magma; the sodium in the part that formed the igneous rocks, and the chlorine in the gaseous solutions. Ages later at the surface of the earth, the sodium was freed by the decay of the feldspar of the igneous rocks, and the chlorine escaped to the surface during volcanic eruptions. Then the two elements, having a great affinity for each other, combined whenever they came in contact. As the salt formed was readily soluble, it was carried to the sea, where an enormous quantity still exists in the sea water. Beds of salt that were deposited from the sea water are found on the land.

Summary.—Most of the valuable ore deposits of the earth were formed by the gaseous solutions given off from a magma as it cooled and became an igneous rock. The solutions entered openings in the rocks and deposited the valuable metals they carried as veins and many other

types of deposits. Such deposits are said to be of magmatic origin. Later processes formed secondary deposits from these primary ones.

SUMMARY OF VOLCANISM AND IGNEOUS ROCKS

Magmas move outward from interior parts of the earth and give rise to intrusive and extrusive forms of igneous rocks and to associated ore deposits. The four minerals, feldspar, quartz, hornblende, and pyroxene, unite in different combinations to form the primary igneous rocks. These rocks are named with reference to their mineral composition, texture, and color.

CHAPTER IV

WEATHERING OF IGNEOUS ROCKS

The minerals that enter into the formation of the next group of rocks (sedimentary rocks, sometimes called "secondary rocks" because they are derived from the primary rocks) we shall study are quite different from those that compose the igneous rocks. Before discussing the formation of the sedimentary rocks, however, we must consider the source of the materials entering them and the methods by which these materials are transported and deposited. In this chapter we shall study the source of the materials. This source is the various substances that are produced by the alteration of the primary igneous rocks.

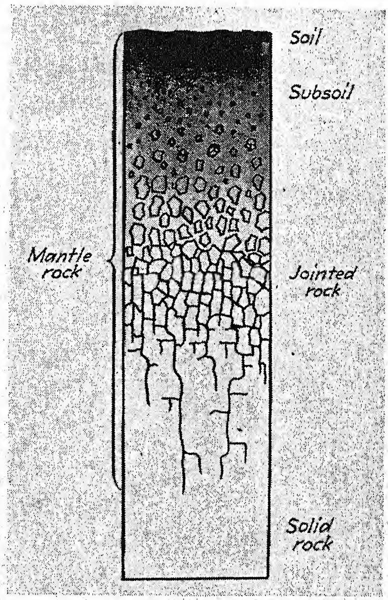


FIG. 63.—Diagram of the mantle rock over an igneous rock.

Our study will begin with the fresh, unaltered igneous rock at the earth's surface and will follow the changes it undergoes in producing the final products. Figure 63 shows this alteration from the solid rock below containing fine cracks and fissures to the much altered layer over it, called the "mantle rock." The lower part of the mantle rock consists of a much cracked and jointed rock which merges into an area containing a mixture of rock fragments and decomposed rock, known as the "subsoil." This also merges into the layer at the surface, called the "soil," which is the final product of the alteration of the rock. This process of breaking up a rock at the surface is called "weathering" because the chief factors in the alteration are the mechanical and chemical agents that are associated with the weather. Weathering, as we shall use the term, includes the mechanical breaking up (disintegration) and the chemical alteration (decomposition) of the rocks. The *agents of weathering* may be classified, therefore, as *mechanical* and *chemical* agents. These agents differ widely in their ability to break up rocks, and individual agents are most effective

under different conditions. In some regions mechanical agents are the most effective; in others, the chemical agents. Such factors as the character of the vegetation, topography, and climate are important in influencing the rate at which the agents accomplish their work.

MECHANICAL WEATHERING

The agents of mechanical weathering are *temperature changes and freezing water*, *growth of vegetation*, *burrowing of animals*, and the *abrasive action of wind, water, and ice*. Of great importance in the work of the mechanical agents are the openings that already exist in the rocks: both those, such as cracks, fissures, and joints, that are due to earth movements; and any original openings, such as the holes caused by the expansion of gases and the minute openings between mineral grains. With these openings in the rock as a beginning or a starting point, the mechanical agents break up the solid rock into fragments ranging in size from enormous boulders to the finest dust. These fragments are as like the original rock in composition as they would be had the rock been put through a crusher. It will be readily seen how this production of rock fragments prepares the way for effective work by the agents of chemical weathering. Mechanical weathering is not finished, of course, before chemical weathering begins, the two processes usually going on simultaneously.

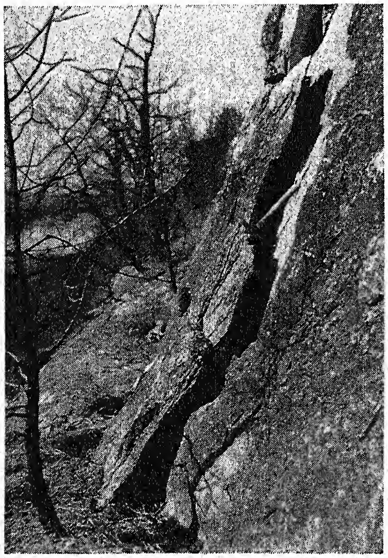


FIG. 64.—Slab of limestone split off face of bluff on Missouri River, Boone County, Missouri. (*Photograph by W. A. Tarr.*)

The Effects of Temperature Changes and the Freezing of Water.—It had long been thought that the cracks and fissures in rocks were in a large measure the result of temperature effects, *i.e.*, that a rock surface expanded on becoming warm under the sun's rays, and, conversely, contracted in the cool night air, the repeated expansion and contraction finally resulting in a crack. Recent studies[1] have shown, however, that temperature effects are probably unimportant in the formation of these openings, and, except in connection with the freezing of water, are ineffectual in enlarging the cracks that have been formed by earth movements. If surface water enters the cracks or joints in a rock and freezing takes place subsequently, the pressure exerted by the ice on

[1] ELIOT BLACKWELDER, The Insolation Hypothesis of Rock Weathering, *Amer. Jour. Sci.*, vol. 26, p. 97, 1933.

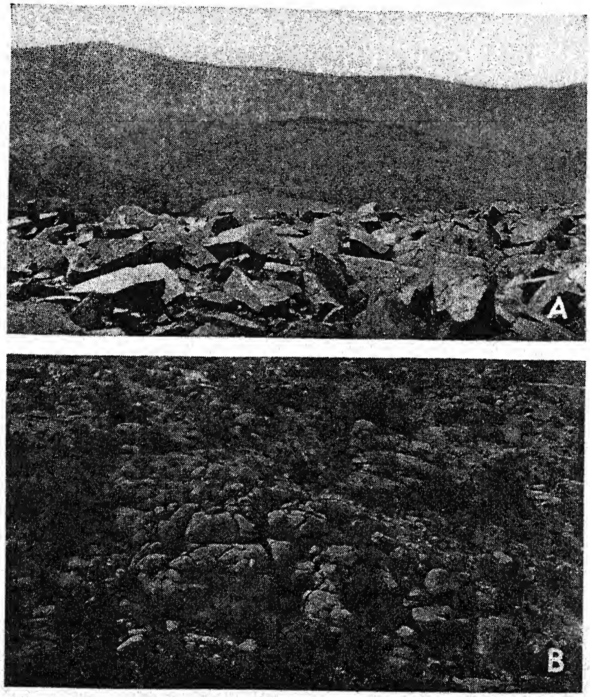


FIG. 65.—(*A*) Angular boulders due to mechanical weathering, top of Pikes Peak, Colorado. (*B*) Rounded boulders due to chemical weathering, at base of Pikes Peak. (*Photographs by W. A. Tarr.*)

FIG. 66.—Abrasive action of running water on granite boulders, St. Francis River, Madison County, Missouri. (*Photograph by W. A. Tarr.*)

the walls of the cracks will aid materially in widening the cracks and so in finally disrupting the rock. This pressure (150 to 200 pounds per square inch) exerted by the ice is due to the expansion (a one-tenth increase in volume) during the freezing process. Figure 64 is a picture of a slab of rock (limestone) being split off a southwest-facing bluff along the Missouri River. This disruption is due to a combination of causes, *i.e.*, jointing in the rock, effects of the freezing of water in the joint, and possibly some aid from gravity. On the tops of high mountains where freezing occurs frequently, great quantities of the angular fragments it produces accumulate, as seen (Fig. 65-A) on the top of Pikes Peak.

FIG. 67.—Ice-abraded surface of a hard igneous rock, Gananoque, Ontario. *(Photograph by W. A. Tarr.)*

Effects of Other Mechanical Agents.—The *growth of roots* in cracks of rocks gradually splits them open and thus aids in their disintegration. *Burrowing animals* also aid in the disintegration of rocks.

By the ceaseless *abrasive action of the wind* (see Fig. 282, page 259), *water* (Fig. 66), *and ice* (Fig. 67), particles of rock are ground off. These pieces are of various sizes but are largely fine material that may be readily attacked by the chemical agents of weathering. The milky color of the streams flowing away from the end of a glacier is due to the large amount of ice-ground rock powder they contain.

Talus Deposits.—At the foot of cliffs or other steep slopes where the bare rock is exposed, the fragments of rock that have been produced by the work of the various agents of mechanical weathering accumulate into what are known as *talus deposits* (Fig. 68) and *rock slides* (Fig. 69). The slope of the talus deposit is usually steep, and it is not only difficult but dangerous to ascend or walk across it. Freezing of water in cracks

of the rocks is probably the most important single force in the creation of this talus material, because by the wedging action of the ice the

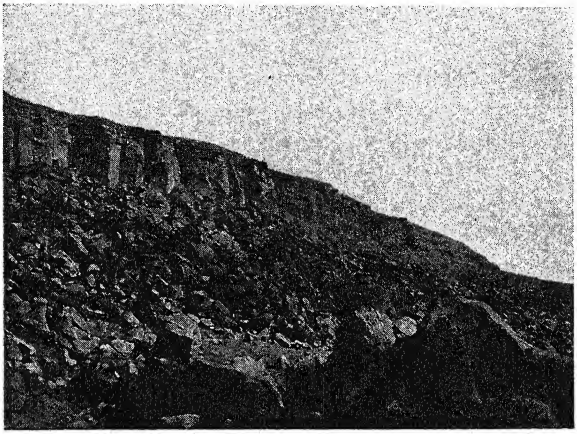


FIG. 68.—Talus slope at foot of cliff which is part of a laccolith, Highwood Mountains, Montana. (*Photograph by W. A. Tarr.*)

fragments produced are loosened and pushed outward until gravity pulls them down. Not uncommonly a large talus deposit or rock slide moves outward from the base of a cliff and may even flow down a valley, whereupon it is called a *rock stream* (see Fig. 154, page 143).

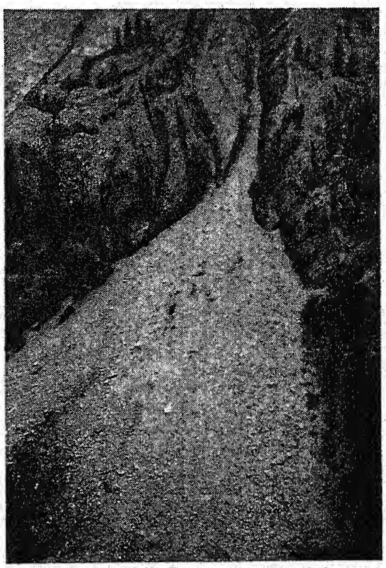


FIG. 69.—Rock slide in mountains above Ouray, Colorado. (*Photograph by W. A. Tarr.*)

CHEMICAL WEATHERING

The chief agents of chemical weathering are *water* and *air*. These agents attack the minerals of the original rock and change them into other minerals, and thus the composition of the rock is entirely changed. The chemical agents may attack and completely alter a rock before it is exposed at the surface, as water penetrates the crust to varying distances, sometimes hundreds of feet. The chief means of entrance to the rocks is furnished by the cracks and fissures which earth movements have developed.

Water is present in the air, from which it falls upon the earth's surface as rain (meteoric water). This water then drains off the surface into rivers or other bodies of water, or soaks into the soil and passes on

downward into the rocks, or evaporates and goes back into the air. Though pure water is a solvent for many substances (for example, sugar and salt), the water as it falls through the air takes up small amounts of oxygen, carbon dioxide, and other gases, thereby increasing its solvent power. The air consists dominantly (four-fifths) of inert nitrogen, but it contains also nearly 21 per cent of oxygen, considerable amounts of certain inert gases, water vapor (in greatly varying quantities), carbon dioxide (3 parts in 10,000 by volume), and smaller quantities of sulfur dioxide, chlorine, ammonia, and even nitric acid. The air penetrates the openings and pores in the rocks at the surface and thus brings all its constituent substances into contact with the minerals of the rock. Also, after bringing these substances down to the surface, the rain water carries them underground, where they aid the water in its work. While it is bringing about alterations in the minerals of the rocks, the water acquires still other substances that increase its solvent power. It is especially apt to acquire sulfuric acid from the breaking up of a mineral (such as pyrite) that contains sulfur, and it acquires organic acids from decaying organic matter on the surface. Water, however, is not dependent upon acids for its solvent power, as it is possible for pure water to effect the complete alteration of a rock.

The chemical effects of the air consist of the union of oxygen, carbon dioxide, and other gases with the substances in the rocks. The oxygen, especially in the presence of water, readily unites with the iron of iron-bearing minerals to form iron oxides. Iron rust is a familiar example of this change. Both oxygen and water are required in its formation, which takes place so rapidly that a clean piece of iron may become rust-covered in an hour or less. This change can be expressed as follows: 2 parts of iron (Fe) unite with 3 parts of oxygen (O) to form Fe_2O_3 = hematite, a very common red iron mineral. In the presence of water (H_2O) 2 parts of Fe_2O_3 (hematite) unite with 3 parts of H_2O to form $2Fe_2O_3 \cdot 3H_2O$ = limonite or iron rust. The union of oxygen with another substance is called *oxidation*, and its union with iron is the only such alteration of common occurrence in rocks. The carbon dioxide of the air does not readily unite with substances, but that contained in water (in carbonic acid, H_2CO_3) can combine with several elements. The process is called *carbonation.*

The most effective agent in rock decomposition is water. Its union with a substance is called *hydration*, an example of which is the formation of limonite, given above. Water attacks the rocks upon the surface, of course, and also beneath it, as a part of the rainfall or *meteoric water* seeps downward and becomes ground water.

The water (whether pure or containing various solvents), upon moving downward and coming in contact with the minerals or particles of rocks, may alter them into new substances. The alteration may be

slight or nonexistent, as in such minerals as quartz and muscovite; or it may be complete, as in feldspar and the mafic minerals. The finer the particles that were formed by the mechanical weathering of the rocks, the easier it is for the water and other chemical agents to alter them. Near the surface, therefore, where the fragments produced by mechanical weathering are finest, the chemical alteration is most rapid. The result of the attack by water is the formation of a group of more or less soluble compounds that are removed in solution, and of a group of insoluble products that are left behind to form the dominant constituent of the soil and subsoil. Any insoluble impurities in a soluble mineral or rock are also left behind.

Character of the Changes Produced during Chemical Weathering

A very fundamental law, called the *law of stability*, controls the changes that occur in minerals at the surface. Simply stated, the law is as follows: *a mineral is stable* (*i.e.*, remains unchanged) *as long as it is surrounded by the same conditions as those under which it formed.* Thus feldspar is formed during the solidification of lava under conditions of high temperature and, if solidification takes place deep within the crust, great pressure. Under the conditions of low temperature and pressure at the surface the feldspar is no longer stable and so is readily attacked and altered by water and air. A corollary of the law of stability as applied to weathered products is that *the new minerals formed are stable at the surface.* This, we shall see, is true, and the new products that arise go into the formation of the dominant types of the secondary (sedimentary) rocks. We shall follow the changes that meteoric water produces in a rock as it works its way down through it.

The outermost zone of the earth is composed dominantly of granite. This rock was undoubtedly one of the most abundant rocks of the surface during the earth's early history, and is at present one of the most common of the igneous rocks found there. We shall, therefore, choose it as the grained rock whose weathering we shall discuss first and in the most detail.

Weathering of a Granite.—An exposed granite surface is attacked by both water and air and the alteration proceeds slowly downward. This downward progress is accelerated by the cracks and joints that had been developed in the rock by earth movements, as these openings permit the chemical agents to penetrate deep into the rock. Such cracks and joints may be small and closely spaced (Fig. 70) or large and widely spaced (Fig. 71). Figures 72 and 65-B show the weathered forms produced in a granite that contained a system of closely spaced joints, and Fig. 73 shows a huge boulder weathered from a granite in which the joints were widely spaced. These cracks and joints (supplemented by the further disintegration due to mechanical weathering) are very

essential in the process of chemical weathering, as granites (and all other igneous rocks) are very impervious and the penetration of water and air would be a very slow process if confined to the openings inherent in the

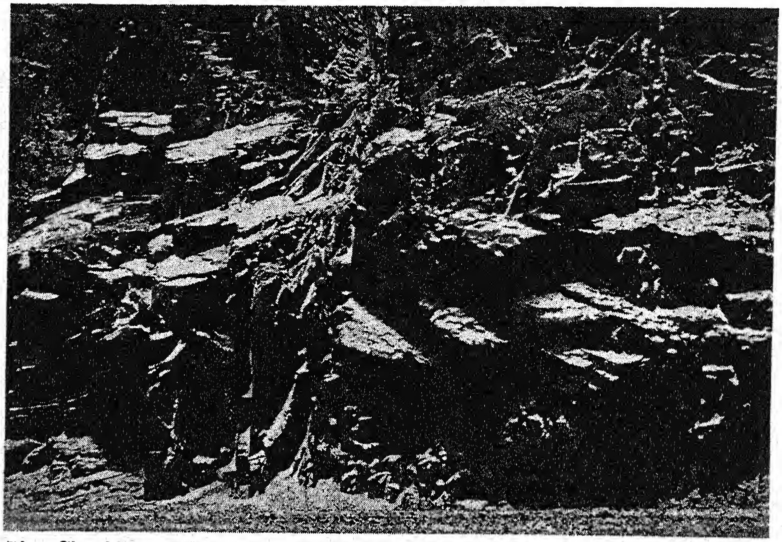


FIG. 70.—Closely spaced joints in porphyry, Hogan, Missouri. (*Photograph by W. A. Tarr.*)

granite itself, *i.e.*, the minute openings between the grains of feldspar and quartz and those along the cleavage planes of the feldspar.

FIG. 71.—Widely spaced joints in granite, Graniteville, Missouri. Ladders are 10 feet long. (*Photograph by W. A. Tarr.*)

The Alteration of Orthoclase to Clay Minerals, Colloidal Silica, and Potash.—The first mineral attacked in granite is the feldspar, because of the openings along its well-developed cleavage planes. The microscope

has revealed the fact that the alteration of feldspar occurs along these cleavage planes on the interior of the mineral, the change to other substances being shown by a cloudy whiteness in the feldspar. It will be

Fig. 72.—Boulders developed by weathering along closely spaced joints, Graniteville, Missouri. (*Photograph by W. A. Tarr.*)

recalled that the feldspars (as a group) are potassium, sodium, calcium, aluminum silicates. Orthoclase is the potassium feldspar and plagioclase the sodium-calcium feldspar. Orthoclase is altered chemically by water

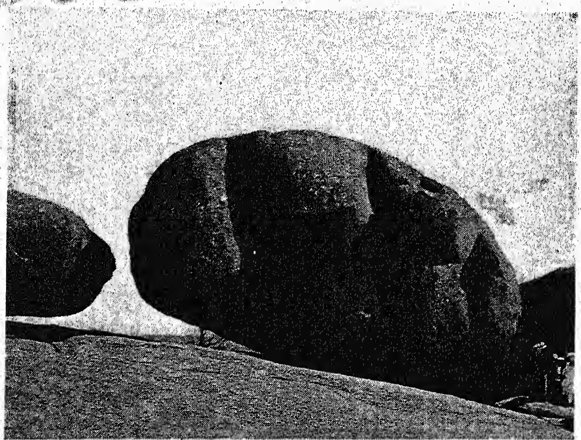


Fig. 73.—Boulder (34 feet long) formed by weathering along widely spaced joints, Graniteville, Missouri. (*Photograph by W. A. Tarr.*)

to some clay mineral[1] (a hydrous aluminum silicate), colloidal silica, and potash (Fig. 74).

[1] Recent studies of the clay minerals formed during most weathering processes in cool humid regions have shown that these minerals are usually of the beidellite-montmorillonite type, the kaolinite type forming in warmer climates. The term "clay mineral" is used in this book in preference to the more specific mineral names and refers to all three minerals.

All the *clay minerals* are relatively insoluble minerals and thus accumulate where they are formed. We have already noted that feldspar is the most abundant mineral in the outer part of the earth, and since all the aluminum in the feldspar eventually passes into the clay minerals, these minerals are probably the most abundant and widespread minerals on the earth's surface. They are the dominant constituents of our soils and of most rocks called *clays* and *shales*. A pure white clay mineral, kaolinite, is the material used in making porcelain, chinaware, and pottery. It should be noted that the aluminum in any mineral, during weathering, usually goes into the formation of these clay minerals.

The silica freed from the feldspar during its decomposition is a soluble compound and is called *colloidal silica*. It is thus very different from

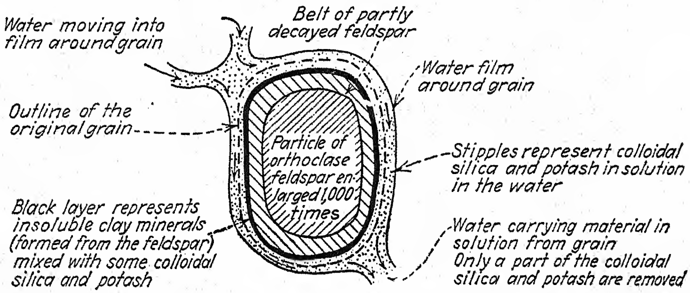


FIG. 74.—Sketch of a particle of orthoclase feldspar undergoing chemical alteration What would the water carry away if the mineral were plagioclase feldspar?

quartz (SiO_2), which is a crystalline mineral and very insoluble. Colloidal silica is set free whenever any silicate breaks up chemically. It is liberated as minute invisible particles that readily unite with water, and this ease of union aids the water in removing the silica particles from the mineral that is being altered. With the elimination of some of the water, colloidal silica forms a gel. Although soluble, much of the colloidal silica remains behind in an intimate mixture with the clay minerals and, therefore, due to the water in the colloidal silica, the mantle rock and soils (as well as clays and shales) are rendered more plastic or sticky.

The *potash* developed is usually sorbed by the other weathered products and thus remains among the residual materials over a decaying rock. As potash was always present in the soils, plants adapted themselves to its use until it is now an essential plant food. The potash could unite with carbon dioxide, but that it rarely does so is shown not only by its presence in the soils but also by the fact that streams contain only about one-fourth as much potassium as sodium though the quantity of the two elements in the crust is nearly the same. Only about one-thirtieth as much potassium as sodium is found in the sea water. On the other hand, clays and shales contain more potassium than sodium.

The Alteration of Plagioclase into Clay Minerals, Colloidal Silica, and Sodium and Calcium Carbonates.—If the granite contained plagioclase instead of orthoclase the clay minerals and colloidal silica would again be formed during the alteration, but, instead of potassium's being liberated, sodium and calcium would be set free to unite with the water. As sodium and calcium unite with carbon dioxide more readily than potassium does, they would form carbonates: sodium carbonate (Na_2CO_3) and calcium carbonate ($CaCO_3$). As both these carbonates are soluble, they may be carried away by water as fast as they are formed. Sodium carbonate soon becomes changed to a chloride (NaCl, common salt) and in this form finally comes to rest in the sea water. Calcium carbonate is found in the water of streams and in spring and well water. It is the most abundant compound being carried to the sea by the rivers of the world at the present time. We shall encounter calcium carbonate in many different physical forms as our study of the earth progresses. Any mineral containing sodium or calcium sets these elements free when it decomposes.

The Insolubility of Quartz.—Quartz is an insoluble mineral; hence the only change it undergoes during the weathering of the granite is disintegration, the larger quartz grains becoming smaller particles. Quartz is the dominant mineral in sands and gravels.

The Alteration of Other Minerals in a Granite.—Besides the essential constituents feldspar and quartz, granites not uncommonly contain *biotite, muscovite,* or *pyrite. Muscovite,* in the form of very fine scales, is a very stable mineral; it ranks next to quartz in that quality. As a result it is an important constituent of some clays and shales, for the thin, flat muscovite flakes are easily carried away by streams or wind.

On the other hand, *biotite,* containing iron and magnesium, is even more readily altered than the feldspar. As a rule any iron-bearing mineral is apt to alter easily, the iron uniting with oxygen to form the iron oxide, as shown on page 62. The addition of water to biotite causes it to change easily into brown biotite and then into a green scaly mineral called *chlorite,* which finally alters to *iron oxides, clay minerals,* and *silica.* Biotite contains magnesium, which unites with carbon dioxide as readily as calcium does, and the resulting *magnesium carbonate* ($MgCO_3$) is carried away in solution. From biotite we get, therefore, two new alteration products in the decomposition of granite: the iron oxides, which are very insoluble and remain in the soil; and magnesium carbonate, which is removed.

Pyrite (FeS_2) a hard brass-yellow mineral (called "fool's gold") is very common in small amounts in granites and all other rocks. This mineral alters to the *iron oxides,* freeing the sulfate radical SO_4. The latter readily unites with calcium, magnesium, potassium, or sodium to form soluble compounds that may be readily removed in solution.

These sulfate compounds, especially *magnesium sulfate* and *calcium sulfate* ($MgSO_4$ and $CaSO_4$), exist in the sea in large quantities.

Substances Added during the Alteration of Granite.—It should be noted that in the alteration of the feldspar of the granite only *water* and *carbon dioxide* were added to form the new minerals. In the weathering of the iron-bearing minerals biotite and pyrite, *oxygen* was added to unite with the iron. The quantity of these three substances needed to alter a granite is well illustrated by the following example of the weathering of a granite (Fig. 75). The fresh granite contained about 70 per cent of feldspar, 23 per cent of quartz, 5.5 per cent of biotite, and some clay minerals. A study of the altered product of this granite by Leith and Mead[1] showed that there had been added to 100 grams of the fresh

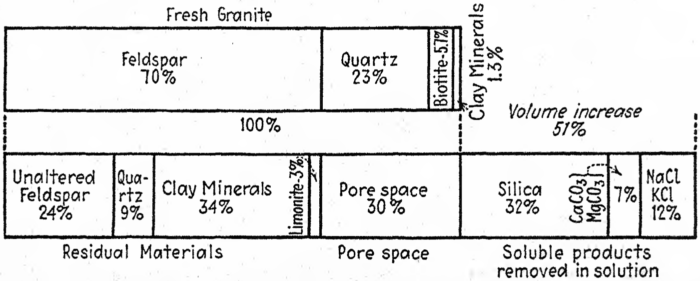


FIG. 75.—Diagram showing the original mineral composition of a biotite granite from Georgia, and the alteration products due to weathering. Note presence of unaltered feldspar in residual (insoluble) materials, and pore space developed by leaching out soluble products. Note also volume increase due to formation of soluble products. (*Data from Leith and Mead, "Metamorphic Geology."*)

granite 6.03 grams of water, 2.74 grams of carbon dioxide, and 0.14 gram of oxygen, a total of 8.91 grams. Since water furnished more than two-thirds of the new substances added, hydration was the dominant chemical change in the process.

The volume of the altered product resulting from the weathering of the granite greatly exceeded the volume of the fresh granite, and the quantity (8.91 grams or about 9 per cent of the volume of the unaltered granite) of the materials added does not account for all of this increase, which is 51 per cent (including the percentage increase due to the pore space produced). This unaccounted-for increase in volume is due to the fact that the new minerals formed are greater in volume for the same weight of material than the original minerals of the granite. This expansion greatly aids in the disruption of the rock.

Altered Zone Produced in the Granite.—The various changes we have been considering produce an altered zone on the surface of the granite (if exposed at the earth's surface) and also extending inward from the

[1] C. K. LEITH and W. J. MEAD, "Metamorphic Geology," 1915, p. 14 (Henry Holt and Company, N. Y.).

cracks and joints. The thickness of this zone depends upon the depth to which the water and air can penetrate the granite, and this depth varies not only with the size and number of the cracks and fissures in the granite but also with the size of its grains, its porosity, and the accessory minerals it contains. The chemical changes taking place in this zone, aided mechanically by the freezing of water in openings, form

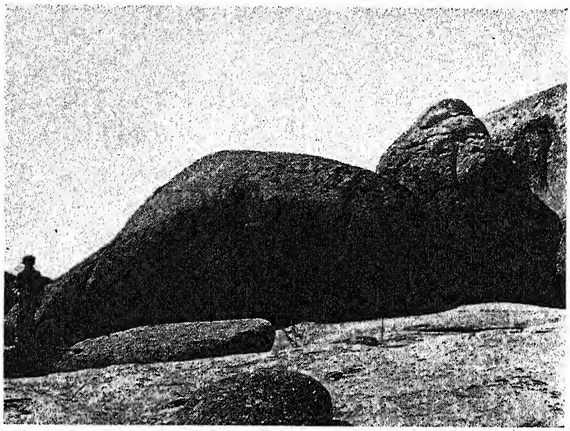


FIG. 76.—Granite boulder showing roughened weathered surface, Graniteville, Missouri. (*Photograph by W. A. Tarr.*)

a layer of altered rock that may disintegrate grain by grain, producing a roughened surface (Fig. 76). This partly altered, loosened material is called *gruss*. If the granite (or other grained rock or a dense rock) is exposed at the earth's surface, a shell may split off as a unit at the depth of maximum alteration (A-B, Fig. 77). This process is called *exfoliation* (Figs. 77 and 78.)

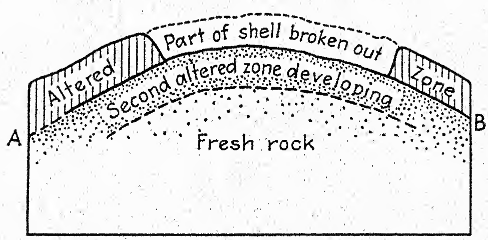


FIG. 77.—Diagram showing development of chemically altered zone in outer part of a rock, and formation of a shell that finally splits off (exfoliation).

Summary.—The alteration of a granite by chemical weathering proceeds as follows: (1) water (with or without carbon dioxide and oxygen) enters the rock along the cracks and fissures produced by earth movements (and further developed by mechanical weathering) and penetrates, also, the minute spaces between and within the grains; and (2) the water reacts with the feldspar (and other minerals, except quartz) to form new

alteration products, of which some are stable and insoluble (as the clay minerals), and some are soluble and are removed partially (as potash and colloidal silica) or entirely (as calcium and sodium carbonate). The new minerals formed have a larger volume per unit weight than the original ones had, and this fact is largely instrumental in causing the granite, before complete decomposition, to crumble into grains (gruss) or scale off in shells (exfoliation).

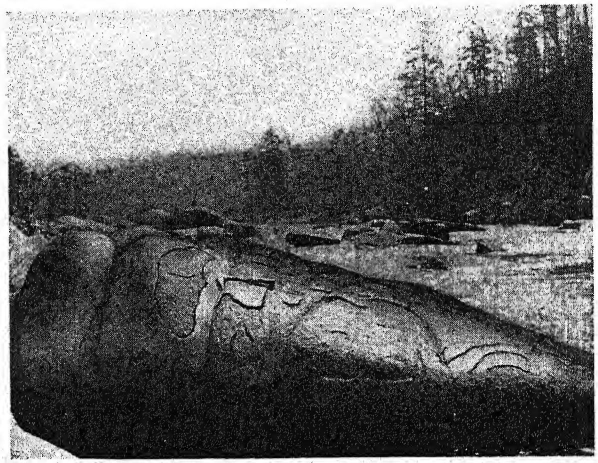


Fig. 78.—Large boulder of granite undergoing exfoliation, St. Francis River, Madison County, Missouri. (*Photograph by W. A. Tarr.*)

Weathering of Diorite and Gabbro.—Diorite and gabbro are the two most common grained igneous rocks next to granite. These rocks contain feldspar, but also one or both of the mafic minerals hornblende and pyroxene. The feldspars alter, of course, to the same minerals they produce in the weathering of granite, so we need only discuss now the weathering of the mafic minerals.

Hornblende and *pyroxene* are calcium, magnesium, iron, aluminum silicates. The aluminum goes into the formation of *clay minerals;* the iron unites with oxygen and water to form the two *iron oxides, hematite* and *limonite;* the *calcium* and *magnesium* form *carbonates* or *sulfates;* and some *colloidal silica* is liberated. The soluble compounds, colloidal silica and the calcium and magnesium compounds, are removed in solution; and the clay minerals, stained red, yellow, or brown by the iron oxides, are left behind.

The soil over either a diorite or a gabbro consists dominantly of clay minerals, and hematite and limonite which give it various colors. It does not contain quartz, of course, and is a heavy soil. As a rule such soils are not so fertile as are those derived from granites. If much organic matter is present in these soils, it will mask the color of the iron oxides and the soil will be gray or black, depending upon the amount of the iron oxides present. The topsoil, which contains the greater part of

the organic matter, of course, may be black, while the subsoil below is a deep red.

Weathering of Felsite, Basalt, and Obsidian.—Our discussion of the chemical weathering of igneous rocks would not be complete without our mentioning the alteration of the dense and glassy rocks. Though the minerals in these rocks cannot be recognized, it is known from their chemical composition that they contain the same eight elements (oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium) that go into the composition of the grained rocks.

The *felsites* (of the dense rocks) are most nearly similar chemically to the granites and certain diorites. The soil over a felsite, therefore, consists largely of *clay minerals,* with *colloidal silica* and *potash.* If a mafic mineral, such as biotite or hornblende, were present in the felsite, some *iron oxides* would develop and color the soil to some degree. The soluble *carbonates and sulfates of sodium and calcium* are formed and removed in solution. Quartz would be lacking in this soil unless the felsite were a porphyry with quartz phenocrysts.

The dense rock *basalt,* which corresponds chemically to gabbro, produces a soil rich in *iron oxides. Clay minerals* result from the alteration, their abundance depending on how abundant aluminum minerals were in the basalt.

The decomposition products of the glassy rock *obsidian* are the same as those of felsite, as it also corresponds to granite in composition.

Summary.—We may sum up our findings of the weathering of the chief minerals of igneous rocks in chart form as follows. It is readily

Weathering of Feldspars, Quartz, Hornblende, and Pyroxene

Mineral	Composition	Products removed in solution	Products left behind in the soil
Orthoclase and Plagioclase feldspar	Potassium Sodium Calcium Aluminum Silica	Sodium carbonate (Na_2CO_3) Sodium sulfate (Na_2SO_4) Sodium chloride ($NaCl$) Calcium carbonate ($CaCO_3$) Potash (KOH), small amounts Colloidal silica ($H_2O.SiO_2$)	Clay minerals (hydrous aluminum silicates) Potash Colloidal silica
Quartz	SiO_2		Unchanged quartz
Hornblende and Pyroxene	Calcium Magnesium Iron Aluminum Silica	Calcium carbonate Calcium sulfate ($CaSO_4$) Magnesium carbonate ($MgCO_3$) Magnesium sulfate ($MgSO_4$) Colloidal silica	Clay minerals (hydrous aluminum silicates) Hematite (Fe_2O_3) Limonite ($2Fe_2O_3.3H_2O$) Colloidal silica

seen from the chart that the total number of alteration products from five different minerals is small, and that they (the former) are easily divisible into two groups based upon their solubility. It should be noted that the soluble alteration products may be carbonates, sulfates, or chlorides, and that sodium goes into the formation of all three. Calcium and magnesium also form both the carbonate and sulfate. Very large quantities of these soluble products are removed from the land annually by the streams.

Intermediate Alteration Products of Weathering.—During the weathering of any igneous rock several minerals, or compounds, intermediate between the original and the final product may form. The

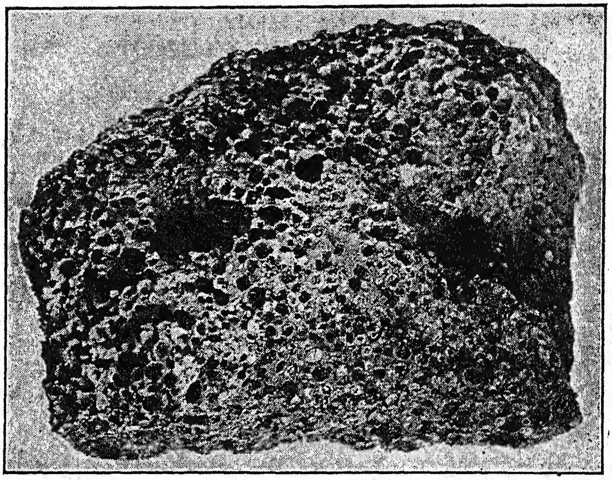


FIG. 79.—Bauxite from Arkansas. Two-thirds natural size. (*From Tarr "Introductory Economic Geology."*)

process of their formation is too complicated to be discussed here, but one or two of the commonest products may be mentioned.

There is good evidence for believing that a *fine-grained muscovite* may form during the alteration of orthoclase feldspar. As it is a very fine scaly mineral, it is easily removed from the soil by wind or running water. Both biotite and the mafic minerals may alter to *chlorite*. This green mineral may be so abundant as to give the rock of which it is a constituent a green color. Olivine, which may occur in gabbro, alters to a common green mineral, *serpentine*. This mineral may be so abundant as to form a rock mass; for example, the great serpentine rock area along the northern California coast. A fibrous variety of serpentine, called *asbestos*, is widely used for many purposes in which resistance to fire and heat is required.

Final End Products of Chemical Weathering.—As we have seen, clay minerals, quartz, colloidal silica, and the iron oxides are the normal insoluble end products of weathering; and these are the minerals produced

during weathering over most of the earth. It has been observed, however, that under conditions which favor long-continued attack by water even the stable clay minerals will undergo decay. This alteration of the clay minerals produces a soluble colloidal silica, which is removed; and an insoluble hydrous aluminum compound, which is left behind. The latter compound is known as *bauxite* ($Al_2O_3.2H_2O$), and is the chief source of the metal aluminum (Fig. 79). The soluble potash which has been sorbed by the clay minerals is removed in solution when this long-continued chemical weathering occurs; even quartz, which, as we have seen, resists all ordinary weathering attacks, is finally converted into colloidal silica and removed by solutions. The *iron oxides*, however, resist even these long-continued attacks of weathering, and so there remains upon the surface a mass of bauxite and iron oxides, which forms a very unproductive soil. If the iron oxides are the more abundant, the residual deposit is red and is known as *laterite*. The final end product of iron-bearing rocks, such as gabbros and basalts, is this product. It occurs abundantly in the tropics and the warmer parts of the temperate zones. If very little iron was present in the original rock, the residual deposit would consist mostly of bauxite.

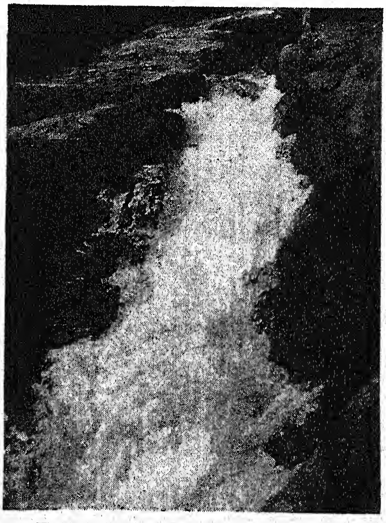


FIG. 80.—Channel of stream produced by the rapid weathering of a basalt dike, Madison County, Missouri. (*Photograph by W. A. Tarr.*)

Rate of Weathering.—The decomposition of a rock is a slow, complex, and variable process, and depends upon many factors, such as mineral and chemical composition, texture, mode of occurrence, and the climate of the region in which the rock is exposed. Some portions of a rock may be more readily attacked by the agents of weathering than other portions a few inches or a few feet away. This might be due to a greater solubility of that portion, to the presence of minerals that decompose easily (as iron-bearing minerals), or to the presence of a mineral (like pyrite) whose decomposition would liberate a strong acid (sulfuric) that would dissolve the other minerals.

The igneous rocks weather very slowly; a lava flow may show very little change on the surface after 100 or 200 years. Many hard igneous rocks that were worn smooth by glaciers show little evidence of weathering since the retreat of the ice, which was many thousands of years ago. As igneous rocks are also very resistant to cracking and jointing, this scarcity of openings helps to make their weathering slow. In general dark-

colored rocks weather faster than light-colored rocks. Dikes of basalt may weather faster than the rocks around them and form depressions (Fig. 80), but this is usually not the case for they commonly weather more slowly and then stand out as ridges or walls (see Figs. 14 and 15, page 18).

No time value can be assigned to the rate of weathering; observations made on rocks used in buildings show a wide range. A rock that undergoes a rapid change in a moist climate will last many times as long in a dry climate. The Egyptian obelisk in Central Park, New York City, had stood unaltered in Egypt for 33 centuries, but began to show signs of decay within a few years after being brought to this country in 1881. Monumental stones in cemeteries also furnish clews to the rate of weathering.

ECONOMIC IMPORTANCE OF WEATHERING

It can be safely stated that the process of weathering is of more importance to man than any other of the geologic processes, for it produces the *soil* upon the products of which man is absolutely dependent for his existence. The story of weathering, as developed above, is the story of soil formation. This process is very slow but it is continuous. All rocks eventually break down and contribute material to the soil. However, the rate of erosion in a given area may be so rapid as to remove the weathered materials as fast as they form and thus leave the unaltered rock bare.

Because soil formation is a slow process and erosion a much faster one, man must conserve the soil and endeavor to stop its erosion. As long as a field has a covering of grass or trees soil erosion is slow, but cultivated fields are exposed to excessive wash after heavy rains, and thus it is necessary to exercise care in farming sloping fields. The gullies widely prevalent in fields in this country testify to a lack of such care and the consequent great damage being done to farm land. Muddy and overloaded streams and rivers tell the same story.

Weathering processes are of further economic benefit to man, as they aid in bringing about a concentration of valuable minerals, such as *gold*, *platinum*, and *gems*, by breaking up the rocks enclosing them. These minerals are very insoluble and also are heavier than the minerals associated with them. As a result they can be easily concentrated by the removal of the other substances. Rarely, the wind may do this, whereupon the concentrated product is known as a *wind placer*. The only wind placers of importance are found in Australia. Streams readily sort the materials that find their way into them and concentrate the heavy minerals along the bottom of the channels. Thus a stream in crossing a gold-quartz vein collects the freed gold in the channel, forming

a gold placer. Sands and gravels have been found that contained $200 or $300 worth of gold in one quart of sand, but such placers are rare.

Another result of weathering of economic value is the formation of *enriched copper deposits*. If a rock containing a small amount of copper is exposed at the surface, meteoric water may dissolve the copper, carry it downward, and redeposit it in a much smaller area. For example, small amounts of copper contained in a thickness of 100 feet of rock form a much richer deposit when redeposited below in a thickness of 10 feet.

SUMMARY

Weathering is the process by which rocks are altered through mechanical and chemical means. Any igneous rock may break down and in so doing form both soluble and insoluble compounds. The soluble compounds are removed by ground water, and the insoluble compounds are left behind to form the soil. If the weathering of the rock keeps pace with the removal of the soil, a soil is maintained; if not, the bare rock is exposed.

The composition of the mantle rock and soil is dependent upon the character of the underlying rock, but essentially all soils contain, in different proportions, the insoluble products of weathering: clay minerals, quartz, and the iron oxides, together with soluble colloidal silica and potash. If chemical weathering can continue uninterrupted by erosion, the final products are the most insoluble products formed from rocks, *i.e.*, iron and aluminum oxides.

We are next to consider the removal of the products of weathering by the different agents, and then their deposition as the sedimentary rocks.

CHAPTER V

INTRODUCTION TO THE PHYSICAL AGENTS

Our study of the earth thus far has dealt only with its composition. We have seen that the outer part is composed dominantly of igneous rocks, and that as soon as these rocks are exposed to the climatic conditions existing at the surface they undergo an alteration by which they are converted into a group of materials that are stable at the surface. We have seen also that these alteration products formed by weathering consist of both soluble and insoluble materials, and that the insoluble materials form the mantle rock, which is a loose, porous aggregate of minerals and rocks easily removed by any agent.

The next subject in our study is these agents of removal. They are called *physical agents* because their work is accomplished by mechanical and chemical means which are physical processes. If it were not for these agents, the surface of the earth would become covered with a mantle of loose rock. But variations in the temperature and composition of the atmosphere, coupled with the distribution of land and water and of mountains and plains, produce winds and rainfall, which are the source of all the physical agents.

In order to accomplish work, the physical agents must be in motion, and the greater their velocity the greater their ability to do work. Motionless air would not move the finest particle of dust, and motionless water would not carry the finest particle of mud. Quiet water might take material into solution, but it would soon become saturated and unable to dissolve more material and so even its chemical action would cease. But, as we have said, variations in temperature of the air cause winds and, given a sufficient velocity, wind will sweep a land surface bare. Also, a stream of water having great velocity will sweep away man-made structures and boulders of enormous size. If water that is dissolving substances in the rocks keeps moving, immense caverns will in time be formed.

The *wind* not only accomplishes much work (*i.e.*, removes much material) itself but it is the indirect agent in accomplishing much more, as it carries moisture-laden air everywhere. The rain formed from this moisture is the source of two great modifying agents: part of the rain runs off over the surface and becomes the *streams*, which are the most important physical agents in shaping the surface features of the land; another part passes beneath the surface to become the *ground water*,

which also accomplishes a tremendous amount of work. The streams do their work dominantly by mechanical means, and the ground water dominantly by chemical means. Another of the great physical agents is the *ocean,* which is the result of the accumulation of the water of the earth's surface in the low places. Although not so effective an agent in shifting material as the streams, the ocean performs a share of the physical work of shaping the earth's surface. Lastly, rain water in the form of ice, *i.e.*, as *glaciers,* may also become a great eroding agent.

These physical agents, wind, streams, ground water, the ocean, and glaciers, we have said, perform work, which we understand to be the removal of the material of the earth. We may well ask what is the end or object of all this work, and the answer is that it is *to reduce the land to the level of the sea.* When these agents have accomplished this end (they never have and probably never will, because of factors operating on the interior of the earth) and water thus covers the surface of the earth, the rainfall, snowfall, ground water, waves, and wind will be useless. The wind might create waves but they would roll ceaselessly and uselessly around the world. The work of the physical agents would be over.

The common objective of all these agents, however, as long as there is land, is to attack it and cut it down. In the accomplishment of this purpose there are three steps which all of the agents follow: (1) removing the material, (2) carrying it elsewhere, and (3) depositing it. Removal of material, the agents accomplished in two ways, *i.e.*, *mechanically* and *chemically.* Bits of rock are loosened mechanically by abrasion, or wearing away, just as a metal is worn away by passing a file over it. Chemically the rock is attacked by being dissolved (corroded) by the agent of removal. Streams, waves, wind, and ice, *i.e.*, all the surface agents, are constantly abrading the rocks, and below the surface ground water is just as steadily dissolving them. Each of these agents is a moving agent and thus the second step in the process is accomplished, for as the agent moves on it carries with it the material that has been loosened from the rocks. The transportation by the surface agents is always downward toward the lowest points of the surface. These two phases of the work of any of the agents, *i.e.*, the removal and transportation of material, are commonly called *erosion.* Finally, on account of a decrease in the velocity, the load of material is deposited. Some deposition takes place, however, by chemical means, *i.e.*, by ground water and, under certain conditions, the ocean.

These agents are forever at work. They vary in effectiveness from time to time and they differ from one another. The deposits formed are temporary, until deposition finally takes place in the ocean. The amount of earth materials emptied into the sea is enormous. Clarke has estimated that the amount of material annually carried to the sea in solution by the streams is 2,491,585,000 tons, or an average of 62.3 tons from each

square mile of the 40,000,000 square miles on the earth's land surface. The quantity of material carried mechanically each year by the streams he has estimated at 16,000,000,000 tons, or 400 tons per square mile of the earth's land surface. Other agents besides the streams are also contributing material to the sea, though in minor quantities.

With this brief introduction to the study of the physical agents which are engaged in a ceaseless struggle to reduce the land surface to the level of the sea, we shall turn to the detailed study of each. We shall study first the streams and next the ground water, as these two agents furnish most of the materials for deposition in the ocean. We shall then study the ocean as the place of deposition and then the deposits formed there, *i.e.*, the sedimentary rocks. The features formed by wind and ice are transitory forms that may be produced on any land surface, so we shall study them after we have finished our study of the rocks.

CHAPTER VI

WORK OF RUNNING WATER

Rainfall.—Running water is the main agent in shaping the earth's surface, but its importance is not appreciated except by those who have studied the processes involved. It is also of primary importance in transporting earth materials from higher lands to lower and depositing them or delivering them to oceans and lakes. Running water and its

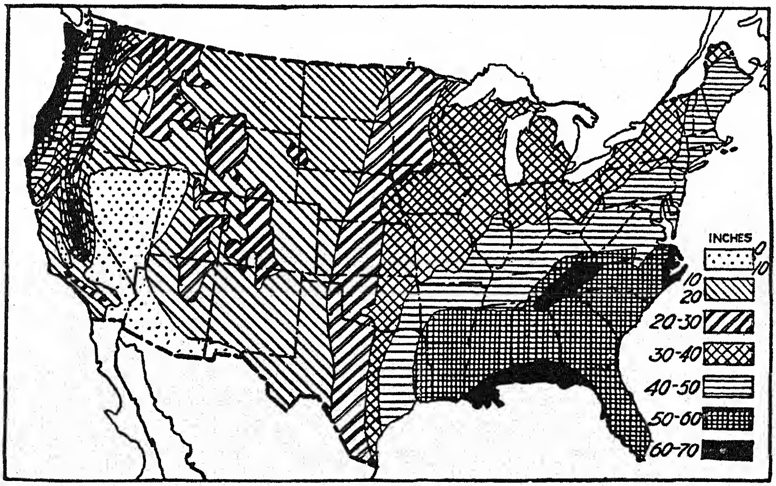


FIG. 81.—Outline map of the United States, showing distribution of mean annual rainfall. (*After Fuller. Courtesy of U. S. Geol. Survey.*)

work are dependent on two things: first, that there be land high enough to give some gradient for the water to flow down; second, that there be a source of the water. The water's source is rainfall. Owing to various causes, rainfall is unequally distributed over the earth, ranging from a small shower once in four or five years, as in the desert of Atacama in Chile, to nearly 500 inches in the upper Amazon in South America and in parts of India.

Run-off.—The water that falls on the land either runs off, sinks into the ground, or is evaporated and taken into the atmosphere. The run-off is most readily observed, and it depends on several factors, the most important of which is the slope of the land on which the water falls. If the slope is very steep, nearly all will run off. In high mountain regions the run-off ranges up to 80 per cent of the rainfall, whereas in

large, relatively level regions the run-off may be less than 1 per cent, with the amount of rainfall the same in both cases.

The rate of rainfall is of great importance in determining the amount of run-off. Farmers call the very heavy, dashing rains "gully washers," as the run-off is so great that gullies are created in the fields. From a rainfall of 2 inches in an hour most of the water will run off, whereas, if 2 inches fall in a day and the land is dry most of the water will sink in.

The condition of the mantle rock influences run-off. If it is loose and deep a great deal more water will sink in than if it is compact. If it is made of clay most of the water will run off. If it is sand and gravel and the rainfall is slow most of the water will sink in. Run-off is much greater in nonforested than in forested or heavily grassed regions.

In some regions the rainfall comes well distributed through the year, about as much one month as another. Other regions have dry seasons and wet seasons. The western part of Central America has about five months with no rainfall and three or four months with heavy rainfall. The run-off in this case is much greater than where the rainfall is evenly distributed. Some regions of considerable rainfall have insufficient moisture for crop raising, because the rain comes in heavy downpours of a few minute's duration and the run-off is very high. In very dry regions rain may evaporate almost as fast as it falls.

Water that runs off from the land collects into streamlets, and the streamlets join to form larger and larger streams. The most important and constant source of stream water is rainfall that sinks into the ground and reemerges as springs or seeps along valley courses.

Streams Form Their Valleys.—People who have no knowledge of geology frequently raise the question of how valleys and hills were formed. Some take it for granted that they have always existed where they are at present, while others think the earth must have cracked open to form the valleys.

Everyone has observed that in times of flood stream waters are muddy and that they are likely to be clear at times of low water. One may readily find out what makes the water muddy by dipping up some of it and letting it stand. Sand and clay settle to the bottom and the water becomes clear. One-fifth of the volume of very turbid streams may be made up of sand and clay. Streams carry away large amounts of sediments during their flood times. Every average year the Mississippi River carries enough sand and clay to cover a square mile of land surface 268 feet deep. If the Mississippi River worked 100,000 years at the same rate and confined its work to an area 5 miles wide and 5,280 miles long, it would excavate a valley 200 feet deep. If the amount of sediment carried by the river were taken in equal amounts from all parts of the Mississippi basin, the land would be lowered about one foot every 5,000 years.

Farmers are troubled by gullies that form in their fields during times of heavy rainfall. They know that these gullies get wider, deeper, and longer, and that in time they will cut the fields into separate units and become so deep that they cannot be crossed with teams.

It has been observed that a stream breaking loose from its channel and flowing across a valleyless region very quickly forms a trench big enough to contain its waters, *i.e.*, it digs itself a new channel. A conspicuous example of this was the work of the Colorado River in southern California when it broke away from its bed and flowed westward to the Salton Sea. It formed a new valley several hundred feet wide and several feet deep within a few days.

Such things as those mentioned above indicate that streams form the valleys in which they flow, and geologists accept that as a general principle. The questions then arise as to how valleys start and how they grow.

Streams Fit Their Valleys.—In many ways streams fit the valleys in which they flow, but valleys vary greatly in their relationships to their streams and to their surroundings. Streams of the same size may have deep narrow valleys, shallow narrow valleys, deep wide valleys, shallow wide valleys, or any intermediate grades. That the size and shape of valleys do not depend entirely on the size of the streams which made them is as obvious as that the size of an excavation does not depend entirely on the size of the group of men that digs it. Following out the analogy between the digging of an excavation and the making of a valley, the next controlling factor is the length of time consumed in the work. Obviously the longer a stream works in a valley the larger the valley will become. If a stream is given opportunity to start a valley on a new land surface it will first excavate a trench just large enough to contain the normal flow. This would be the case if the Atlantic Ocean retreated so that the Hudson River would have to cross the emergent ocean bottom.

VALLEY DEVELOPMENT

The Infant Valley.—Imagine a nearly smooth area of very gentle slope. At the upper edge a large hydrant is opened and the water allowed to take its own course. The course would be determined by the shape of the land surface, *i.e.*, the direction of flow would be a consequence of the original topography. Over a surface with only slight irregularities the course would be in a nearly straight line down the steepest slope. If the surface rocks were unconsolidated sand and clay or other mantle the water would soon remove enough material to form a channel or valley large enough to accommodate it. The valley would be very steep-sided and narrow, only a little wider than the stream.

Meanders Develop.—Though the valley had a nearly straight course, it would be impossible for the stream to maintain a straight current. Winds would create cross currents, materials would slump in from the sides and divert the current, and various other things would make the current irregular. A current once diverted would strike one of the banks and be deflected from that bank to the other, and thus it would begin a zigzag movement down the valley. Where it struck the side it would remove some of the bank materials and take them as part of its load. Where it crossed its channel it would cause the water above it to slacken its velocity and deposit some of their load. The stream would begin to cut into the bank on one side and deposit on the other, and would finally

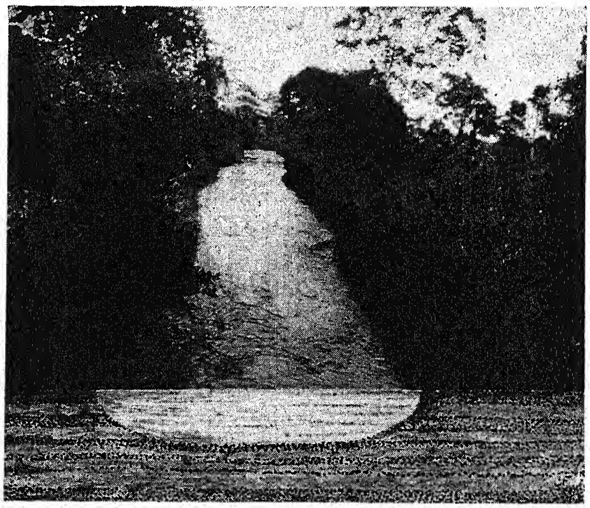
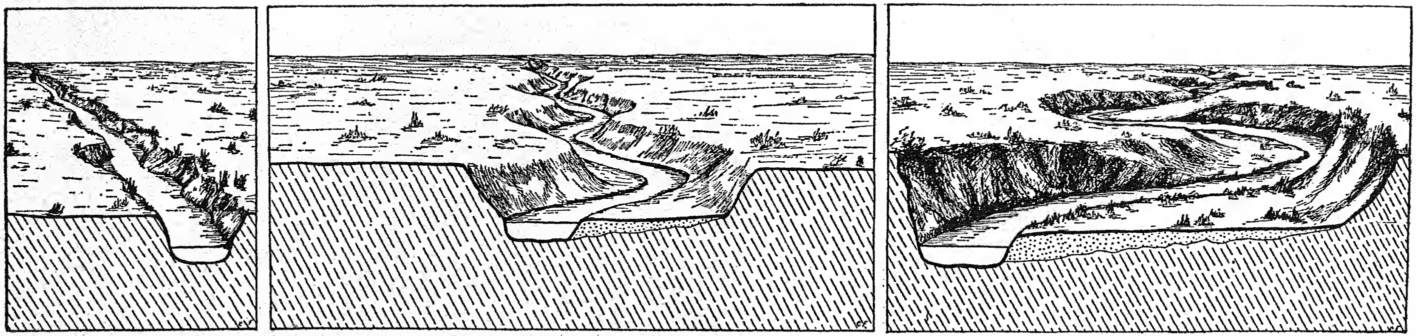


Fig. 82.—An infant valley in Central America. (*Photograph by E. B. Branson.*)

create subsymmetrical curves called *meanders*. Where it cut into the bank it would widen the valley, but as it deposited on the other side it would tend to keep the original width of its channel.

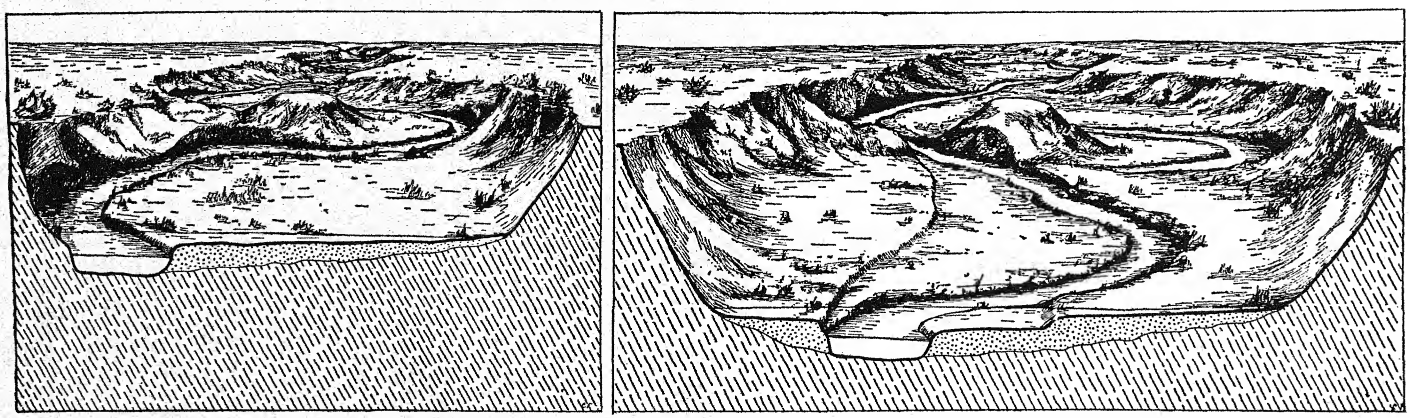
Flats Form in the Valley.—The deposits made by a stream on the inside of meanders build up to about the level of the top of the stream water and are, therefore, below the general level of the region. By the building on the inside of meanders the stream creates flats within the valley that it forms. As it continues to cut on the outer side of the meander and to build on the inner the flat within the valley widens as fast as the valley itself widens.

Streams Straighten and Then Develop New Meanders.—Gradually, as the stream course changes from straight to gently curving to large curves, the valley changes from narrow to wide. But all widening does not take place with the development of one series of meanders. Where the meanders reach the stage that the loop of one nearly touches the loop



A B C

FIG. 83.—The three figures, *A*, *B*, *C*, show the development of a valley from the gully stage to a stage where it has a narrow flat. All stages are young.



A B

FIG. 84.—Development of flats and an isolated hill. (See also Fig. 352.)

of another the stream straightens itself by cutting across the meanders during flood time. During floods the entire width of the valley may be occupied by water and the current takes a rather direct course which may be across the neck of one of the meanders. It may cut a channel across this neck and in low water follow a course through the short channel rather than around the long bend, for some distance resuming its original condition of straightness.

In its straight new course it again begins to meander and first cuts into its own flood-plain deposits, *i.e.*, the deposits that it formed as it created the earlier meanders. The outer part of a meander may finally reach the valley wall and again begin the process of widening the entire valley.

The Meander Cycle.—It is not likely that the completion of a cycle of meanders[1] lowers the bottoms of large valleys as much as 1 inch, and

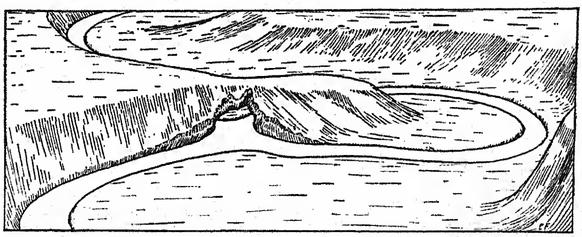


FIG. 85.—How a natural bridge might develop before an isolated hill formed as in Fig. 84.

the deepening of a valley like the Mississippi to some 400 feet below the original level would at that rate take 4,800 cycles of meanders. The greater the velocity of a stream the greater the amount of down-cutting during each meander cycle.

The completion of the cycle of meanders is much more complex than would appear from the above discussion. Actually, the stream is likely to cut off not more than 1 meander in 1,000 at the time of any one flood, and the cycle is completed for one meander long before it is completed for others. In one area three or four cycles of meander development may have been completed before one is completed in another.

Meanders Move Downstream.—The meanders in the valley course tend to move downstream and the outer part of the bend that is cutting in one place in the side of the stream valley may move far enough to connect that bend with the place which the next bend below formerly occupied (Fig. 86, A and B). While the stream is cutting against the outer wall of the valley, it keeps the side vertical or nearly so; but as soon as the stream moves away, weathering processes and slope wash reduce the slope. If, however, the next bend upstream keeps moving down and finally comes to occupy the place where this bend was formerly,

[1] A cycle of meanders is the development from a straight course, through a complete series of meanders to a straight course again.

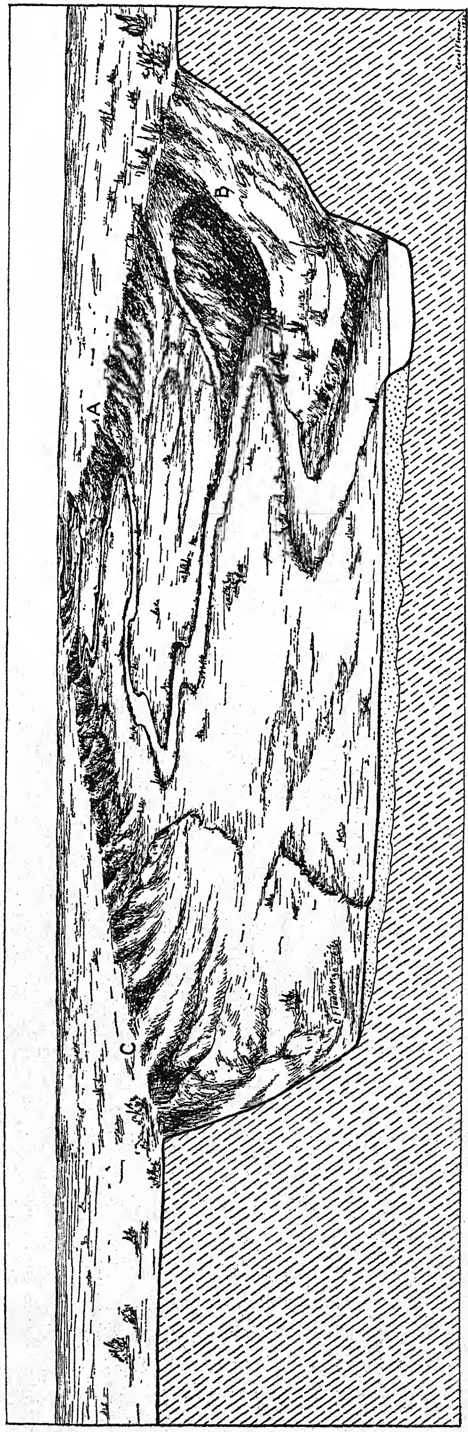


Fig. 86.—A valley in early maturity, a little later stage than Fig. 84.

the stream again begins to cut at the place where the gentle slope had been created and may cut far enough to make that side of the valley vertical again. In this stage of valley development there are alternate vertical and gentle slopes at the same location in the valley and one side of the valley may be steep while the other is gentle (Fig. 86*C*, *B*). As the valley becomes wider and wider, there comes a time when the outer parts of some bends do not touch the valley sides. The meander in moving downstream does not come against the valley side of the next lower meander, and the slope that has had time to be reduced to gentleness since the meander left it is not touched by the next meander which moves downstream, and therefore goes on becoming gentler and gentler during another cycle of meander movement. As the valley widens still farther, fewer meanders touch the outer side and more of the sides come to have gentle slopes. The valley bottom finally reaches about maximum width of the meander belt, a stage illustrated in Fig. 89.

Shifting of Meander Belt.—The meander belt is the area between lines drawn on either side of a valley connecting the extreme outer parts of a series of meanders. The shifting of the entire meander belt now enters into the valley-widening process. As the meander belt shifts in the valley it widens on one side by the outer side of some meanders touching the extreme outer part of the valley. The belt may later shift to the other side of the valley and by changing back and forth many times may widen the valley to many times the width of the belt. The widening would be checked only by the meanders cutting away the divide between their valley and an adjoining valley (Fig. 89).

In Fig. 111 the stream occupies the left side of the valley and the entire valley is three or four times as wide as the meander belt. The widening taking place by meander-belt shifting is much slower than in the earlier stages. The valley of the Mississippi River south of Cairo, Illinois, is more than 60 miles wide and the meander belt is less than 10 miles wide. Many of the large rivers of the world have reached this stage, but many others have not. The Amazon is an example of this stage of valley, the Colorado of an entirely different stage.

The Grand Canyon of the Colorado River.—The Colorado is a very swift stream, and such streams deepen their valleys much more rapidly in proportion to widening than do slow streams. In the Grand Canyon part of the Colorado the valley is 8 to 10 miles wide and about 1 mile deep. The Missouri River valley east of Kansas City is 8 to 10 miles wide by about 300 feet deep and the down-cutting compared to side-cutting in the one case has been 10 times as rapid as in the other. This has not been due in any sense to difference in hardness of the bedrock, as the Colorado has cut through harder rock than the Missouri. One may wonder about the future development of the Colorado Valley. The river is swift and will continue to deepen its valley rapidly in proportion

to widening it for a long period, but gradually the lateral cutting will increase in importance and down-cutting will be slow enough to allow large flats to form. The later history of the valley should differ from that of other valleys only in the great depth that the valley will retain for a length of time long enough to cover the entire history of most rivers. In order to attain the lowest possible grade to sea level, the river must loosen and carry away some 10 times the volume of material that the Mississippi must to attain that grade. On account of aridity

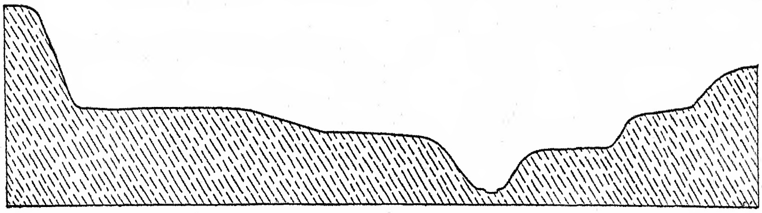


FIG. 87.—A cross-section of the Grand Canyon of the Colorado where it is 9 miles wide and 5,000 feet deep.

the rate of weathering is much slower than in the Mississippi Valley, and most of the loosening of the rock materials will be done by the stream itself. It will require tens of millions of years to bring the Colorado Valley to the stage of the Mississippi.

Size of Stream and Valley.—The widening of the valley depends on the size of the stream in some degree, but a small stream may create a large valley. The increase in width of a valley does not mean that the stream is growing in size. Streams may increase in size by capturing other drainage, but they may become smaller while enlarging their valleys. A common misconception is that the streams that formerly

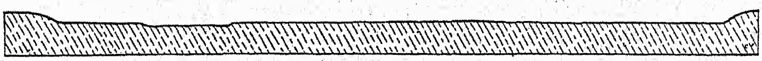


FIG. 88.—A cross-section of the valley of the Mississippi where it is 9 miles wide and 400 feet deep.

occupied valleys must have been much larger than they are now, as the valleys are so much larger than the streams.

Valleys Widen at the Top.—In discussing the widening of valleys at the bottom by lateral cutting, widening at the top has been mentioned only incidentally. The steep sides of valleys produced by side-cutting of streams gradually become gentle after the stream stops cutting against the bottom. Weathering along the top of the valley sides loosens the more prominent parts; they fall to the bottom and gradually the slope is reduced and the angle at the base of the cliff is filled up. The weathering may be accomplished by freezing and thawing, chemical changes, plants, animals, and solution. Water falling near the valley margin runs over the edge as slope wash and carries with it loose materials that

lie on or near the edge. This material is in turn dropped at the base of the cliff and helps to reduce the slope. Gradually the slope decreases, and if the stream does not return to its base, reduction continues until the velocity of the water can no longer carry materials down the slope. The reduction of the slopes of the valley sides is slow, but nearly every

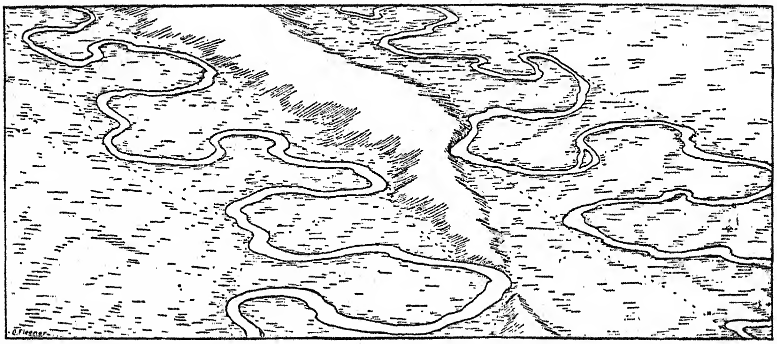


FIG. 89.—Two tributaries that have made wide valleys and have nearly removed the divide between them. The dotted lines indicate the width of the meander belt.

valley furnishes numerous examples of steep slopes where the stream is cutting against the bank and gentler slopes where no lateral cutting has taken place for a long time. Along the Mississippi River one may go directly down the valley slope without encountering perceptible grade

FIG. 90.—Valley development by a moderately slow stream. (*Photograph by Atwood. Courtesy of U. S. Geol. Survey.*)

on one side, cross 5 miles of flat, and on the other side find almost vertical bluffs 200 or 300 feet high. By the time a valley reaches a width three or four times that of the meander belt nearly all side slopes are gentle; finally they become so low that the slope of the valley may scarcely be differentiated from the slope of the sides.

Tributaries Make Flats.—Tributaries work in the same way as the main streams and cut flats continuous with the flats of the main valley. The slopes between the tributaries will have become very gentle by the time the valleys are wide and the entire region may become reduced to stream flats with gentle slopes between and all of the slopes toward streams.

Factors Influencing Valley Development.—The development of valleys depends upon several factors not mentioned in the preceding discussion. The rate at which running water corrades or removes materials from its bottom and sides varies as the square of the velocity. (To corrade is to loosen by friction.) If one stream has twice the velocity of another it will corrade four times as fast. A given object will be struck twice as hard by a unit amount of water, thus doubling the wear; but twice as much water will strike it in a given time, again doubling the amount of wear.

Swift streams have their currents diverted less easily than slow and on that account are likely to develop meanders less rapidly, and the meanders are smaller. Since the widening of the bottoms of valleys is accomplished almost entirely by meanders, swift streams will have narrower valleys than slow ones of the same size. Figure 90 illustrates valley development by a slow stream, while the Big Thompson River (Fig. 91) illustrates valley development by a rapid stream.

The rate of corrasion by streams depends in part upon the amount and kinds of material carried by them. Waters which carry no sediments do little or no wearing. The Niagara River, with great volume and velocity, does little corrading above the falls. The greater the load of sediment carried by a stream the greater its efficiency in wearing rock, up to the stage where the size of the load reduces the stream velocity.

The character of the load is also a large factor in determining the rate of wear. Angular grains wear other rocks much faster than rounded grains and hard particles are more effective than soft particles.

Engineering Control of Stream Erosion.—In attempting to control the cutting of rivers many serious mistakes have been made by engineers. An example in Central America will illustrate this. A railroad was built along a very rapid stream in a narrow valley. At one place a meander started cutting against the solid rock on which the railroad was built, and as the rock was not very resistant, the stream undermined the railroad. The construction engineer attempted to stop this by filling in quantities of material and building concrete walls at the place where the stream was cutting, but the stream cut out the concrete walls as rapidly as it had the other rocks. By filling in a relatively small amount of material in a bend of the meander a few hundred feet upstream, where the water was not swift, the direction of the current could have been

changed so that it would have cut across the neck of a meander and left the railroad safe.

Sources of Stream Load.—During the entire time of valley development streams get more of their load through slope wash than through any other means, and the materials are prepared mainly by weathering

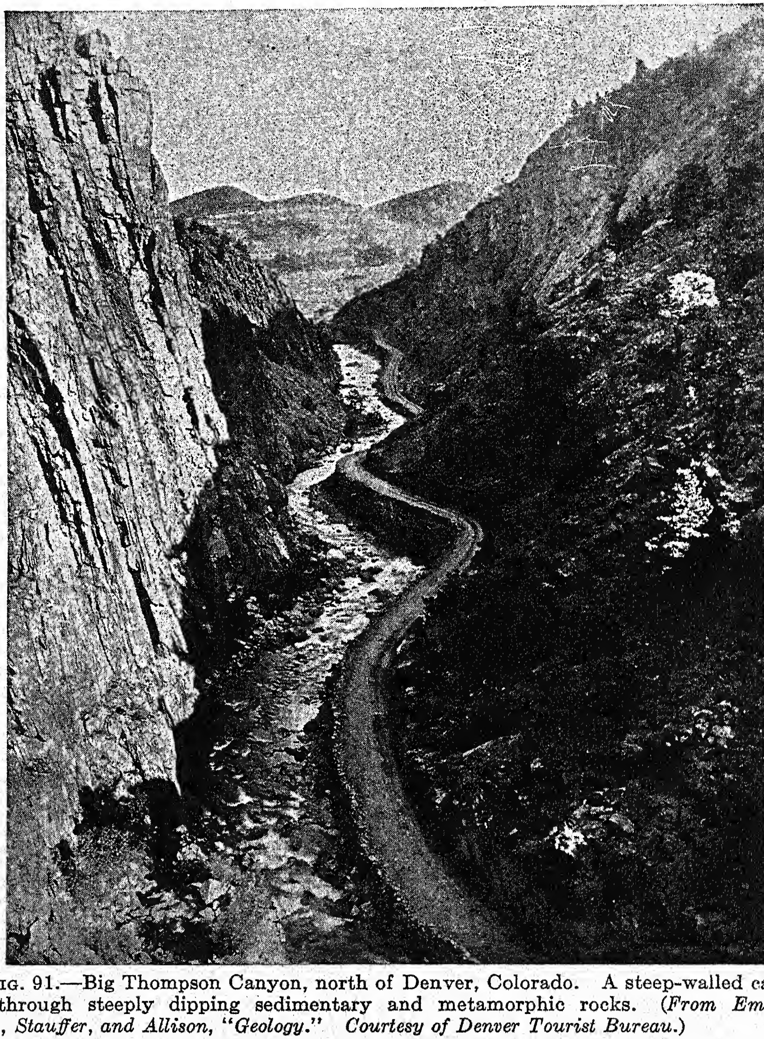


FIG. 91.—Big Thompson Canyon, north of Denver, Colorado. A steep-walled canyon cut through steeply dipping sedimentary and metamorphic rocks. (*From Emmons, Thiel, Stauffer, and Allison, "Geology." Courtesy of Denver Tourist Bureau.*)

processes other than friction. We have found that most of the earth is covered by mantle rock from a depth of a few inches to several feet. During every rain some of this mantle rock is washed into the gullies and small streams, and these carry the material to the main streams. The material which has been produced by weathering is mainly clay and sand, regardless of the kinds of rock from which it originated.

Streams loosen some fragments from the solid rock by their own work. After they have cut through the mantle rock they encounter solid rock, and as very little chemical weathering takes place in the bottoms of streams, they must deepen their valleys by actual wear. They do this by rolling sand and gravel over the solid rock. The rate

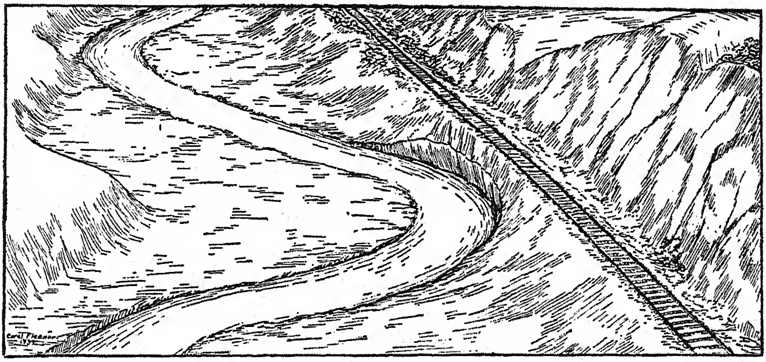


Fig. 92.—A railroad in Central America undercut by a stream.

of wear depends partly upon the kinds of rock over which the stream flows. One may note that along almost any stream parts of the valley are much wider than other parts, and if he investigates the rocks which make up the sides and bottom of the valley he will probably find that the rocks where the valley is narrow are hard and those where it is wide

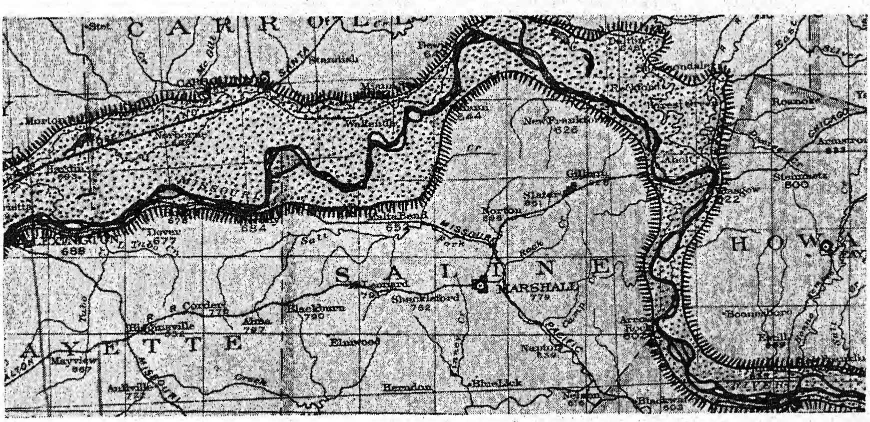


Fig. 93.—Missouri River from Lexington to Boonville, Missouri. Note the abrupt narrowing of the valley near Glasgow.

are soft. A good example of this may be noted along the Missouri River about the central part of Missouri. Maps of the Missouri River valley show that it narrows very abruptly about 75 miles east of Kansas City. Between Kansas City and that place the river flows on shales, while east of there it flows on limestones; it has widened its valley about twice as much in the shales as in the limestones.

Character of Stream Load.—The materials that streams actually wear off the solid rocks are generally different from the chemically weathered materials that come into them by means of slope wash. If a stream flows over granite the little pieces of material that are worn off consist of fragments of granite or of the minerals that make up granite: feldspar, quartz, micas, etc. Slope wash brings mainly the chemically weathered materials, clay minerals, and quartz sand. That streams carry much greater amounts of clay minerals and quartz sand than non-chemically weathered fragments of rock is an evidence that slope wash is more important in furnishing the stream load than is the actual wear of the streams themselves.

HOW STREAMS ATTAIN THEIR COURSES

Extended Consequent Streams.—When one becomes convinced that streams make their valleys the question of how they happen to take their

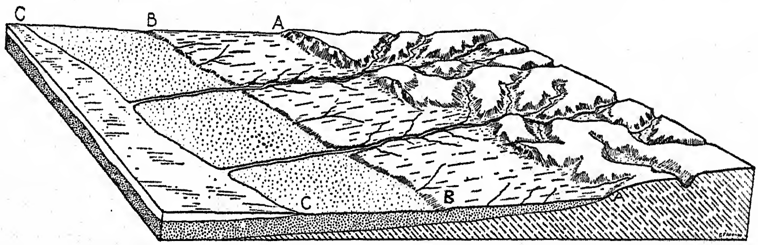


FIG. 94.—Extended consequent streams. The ocean margin ran from *A* to *A* for time enough to form a beach and sea cliffs. It then withdrew to *B-B*, and the streams extended their courses across the newly emerged sea bottom. A second withdrawal of the ocean margin to *C-C* caused the streams to extend their courses again.

courses arises. If the Atlantic Ocean margin should move eastward 100 miles from the east coast of the United States, a rather uniform plain—the old sea bottom—would become land and every stream now flowing into the Atlantic would have to develop a valley across this land. Many streams emptying into the Atlantic along this coast are of large volume and if the sea should retreat 100 feet per day, or 1 mile, or more, the streams would not be left behind but each would follow down the steepest slope of the new land and dig for itself a new valley. (This assumes that the newly formed land would be made of unconsolidated sand and clay, an almost universal condition.)

If you can picture for yourself the emerging sea bottom of mud flats, the edge of the sea moving away from the land about 100 feet per day, and a large river flowing into the sea and keeping its channel across the newly emergent land, you will get an idea of how the courses of most large rivers were attained. In 10 years the sea margin would have retreated about 70 miles and laid bare 70 miles of mud flats. The river would have taken a nearly straight course across this 70 miles, and if the gradient were low the valley across the mud flat would be just big enough

to contain the normal stream water. Flood waters would probably overflow and spread out over the surrounding flats. Every big stream would have such a valley across the newly emergent land.

The Red River of the North took its course in the wake of a retreating margin of a lake, and other streams emptying into the lake from the south took their courses nearly parallel to the Red River. Figure 95 shows the course of the Red River as well as the margin of the old lake. Within relatively recent times Lake Erie has withdrawn several miles from its old southern shore, and the streams entering it from the south form examples, on a small scale, of *extended consequents.* Maps of

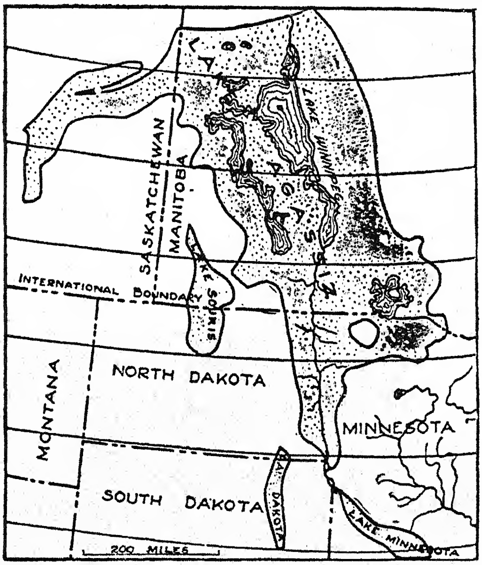


FIG. 95.—Map of extinct Lake Agassiz showing the Red River of the North in an extended consequent valley. (*After Upham. Courtesy of U. S. Geol. Survey.*)

the region show the nearly parallel streams flowing across the old lake bottom.

Consequent Valleys.—Many streams, but not the large ones, take their courses in consequence of the topography rather than as extended consequents. Picture again the newly emergent mud flats of the old ocean bottom between the large extended consequents. These flats would slope gently seaward, in the main, but would have no drainage channels. When rain fell on them, the water would run off through the lowest places and soon form gullies which would end in the main valleys or in the sea margin. The course that the water would take would depend upon the topography, *i.e.*, would be in consequence of the topography. If the rainfall were heavy the gullies would form rapidly and furnish drainage channels for the entire area, but if the rainfall were light it would take a long time to form gullies for all of the area. There

would be many little streams, but they would join to form larger streams in their lower courses.

The two main ways in which streams attain their courses are "extended consequents" for big streams and ordinary "consequents" for the smaller streams, but other ways of valley development deserve mention. In some places the earth has warped down so as to create depressions and these have become stream valleys. The Great Valley of California, through which the Sacramento River runs, had such an origin. Along large fissures in the earth movement has taken place, one side going up relative to the other, and this has created stream courses. Long blocks of the earth have settled down between two fissures and created valleys. The Red Sea is in a depression of this type. Man has acquired the habit of making valleys, the smaller ones as irrigation ditches, the larger as canals. In some cases irrigation ditches have drained the stream from which the water came and have become the main stream.

AGES OF VALLEYS

In a preceding paragraph the valley of a very young stream was called "the infant valley." As streams develop their valleys go through stages of youth, maturity, and old age, and each has its peculiarities. Ages are not considered in years but in terms of conditions of development.

Young Valleys.—The narrow, steep-sided beginning valley is called young, as it is in an early stage of valley development. In the gully stage the young valley will have no flats, or only very small ones. The young valley that has a very swift stream that carries away deposits soon after they form has only temporary flats. Most young valleys have narrow, discontinuous flats, and the deeper the valley the wider the flats may be before a mature stage is reached.

Mature Valleys.—At the stage where flats become continuous from one meander to another, as shown in Fig. 86, the valley is entering the stage of early maturity. The mature stage continues until the valley is several times as wide as the meander belt, and most of the side slopes are gentle. Steep slopes exist along the sides, here and there, where the meander belt has shifted to the side of the valley and the outer sides of the meanders again eat into the higher land, as shown in Fig. 86.

Old Valleys.—The old-age stage of valley begins with wide flood plains and few steep side slopes, and passes to the stage where it is so wide and the slopes of the sides so gentle that it is indistinguishable as a valley. The divides between valleys have become so low that they do not appear as features of the landscape.

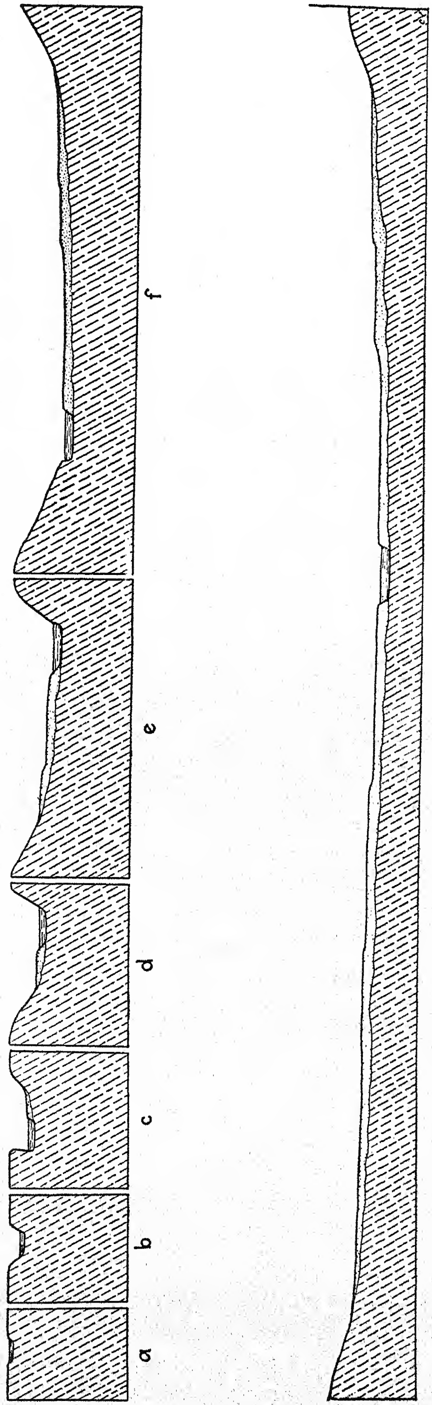


FIG. 96.—Seven stages of valley development. *a*, *b*, *c*, and *d* are young stages, *e* is in early maturity, *f* is mature, and *g* is in early old age.

COMMON FEATURES DEVELOPED BY STREAM EROSION

In the making of valleys streams develop many features of the landscape that are familiar to everyone and others that are unusual. Falls, rapids, terraces, and isolated hills belong in the first group.

Rapids and Falls.—Rapids and falls are both due to stream erosion of alternating hard and soft layers of rock, or to rapidly constructed dams. Where a stream flows from hard rock to soft, it lowers the soft faster than the hard and produces a steep grade from the hard to the soft, resulting in rapids. The rapids increase in grade until the greater velocity of the water over the hard rock causes an equal rate of erosion with the slow water over the soft. This balance may be maintained for long periods of time, and the rapids be lowered without altering their grade. When down-cutting has produced such a low grade on the soft rock that erosion is exceedingly slow, the hard rock is reduced

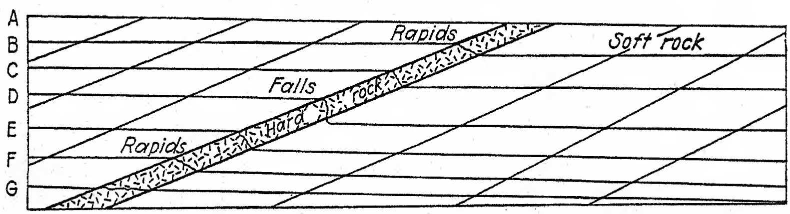


Fig. 97.—A diagram showing development and disappearance of rapids and falls and migration of falls upstream. (*A*) First stage of stream with even grade; (*B* and *C*) rapids develop; (*D*) falls have developed; (*E* and *F*) falls disappear and rapids become less swift; (*G*) the stream is near sea level and is at low grade.

faster than the soft, the rapids gradually decrease in speed and finally completely disappear. If the difference in rate of erosion of the two beds is so great that the face of the hard rock becomes nearly vertical, falls are formed. Rapids are common along streams in young or mature valleys but falls are not.

There are many different conditions under which soft rocks may alternate with hard so as to produce falls. Beds of rocks of different hardness may be horizontal, may dip up streams, may be vertical, or may dip steeply downstream. Igneous rocks may alternate with sandstones, shales, or limestones by intrusions into them or lava flows over them. In every case the soft rocks must be downstream from the hard to cause falls to develop. Under most conditions falls change their location as the rocks forming them are cut down by erosion.

Migration of Falls.—At Niagara Falls the rocks dip slightly upstream, hard limestone beds with shales below. Water running over the falls and striking at the bottom takes on a sort of whirling motion, strikes against the shales, and wears or plucks them out so that the limestone overhangs. When the undermining reaches a vertical

crack in the limestone, part of the rock slumps off and the falls recede by the width of the slumped block. The undermining causes the Canadian Falls to retreat upstream at a rate of about three feet per year. The American Falls, having much less water to work with, move back only about 8 inches per year.

Niagara Falls have migrated upstream from Lewiston, a distance of about 7 miles, and at the rate of 3 feet per year the migration has taken more than 12,000 years. This geological clock, however, is not perfect, since it has been found that in its earlier stages the river was only about half as large as it is at present. If Niagara Falls continue to move upstream they will finally reach Lake Erie, lower the lake about 160 feet, and cease to exist as falls. The rapids, however, will exist until the

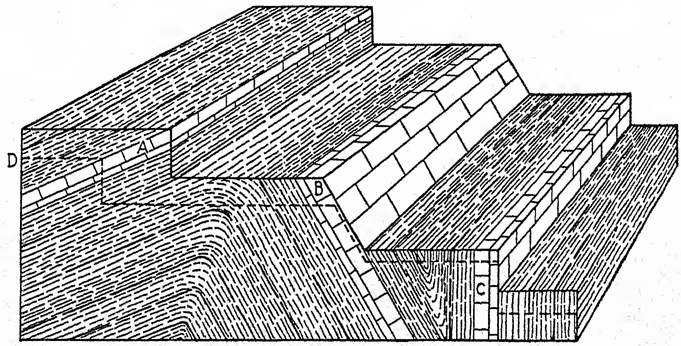


FIG. 98.—A diagram showing conditions under which falls move upstream (*A*) as the stream lowers its bed; move downstream (*B*); remain stationary (*C*). The broken line *D* shows the location of the falls after the stream lowered its channel.

grade between Lake Erie and Lake Ontario becomes low and rather uniform.

In many regions sedimentary rocks overlie igneous. If these are strongly tilted downstream very steep rapids or falls form where the water flows from the igneous on to the sedimentary, even though the slope downstream is much less than vertical. In this case as the river lowers its bed the falls migrate downstream. If the hard layer which forms the falls meets the soft rocks in a vertical plane the falls remain stationary as the river cuts down.

Falls and rapids have proved hindrances to navigation. Many rivers are navigable to some particular falls or some particular rapids. But rapids may not completely stop the navigability of a stream if there is deep water through them. Engineering plans have been completed for canals around the rapids of the St. Lawrence River large enough to allow ocean steamers to reach the Great Lakes.

Terraces.—In all river valleys there are numerous flats terminated on one side by steep slopes which descend to lower flats. Such features are called terraces and are developed where a stream cuts across a meander

and starts meandering again. Terraces are shown in Fig. 99, and the starting of terraces in Fig. 86. We have found that in cutting a valley the stream meanders back and forth across it hundreds and even thousands of times, and as each shift creates terraces, their number is very large. However, as the stream cuts on the outer side of the meander and moves across the valley, it destroys all former terraces as far as it goes. It may not cut to the extreme side of the valley and therefore may leave some of the terraces.

In some valleys there are very wide flats a few feet to possibly 200 to 300 feet higher than the next flats below, and these make striking features. Such terraces develop in mature or old valleys where the stream velocity increases and cuts a deeper, narrower valley within the

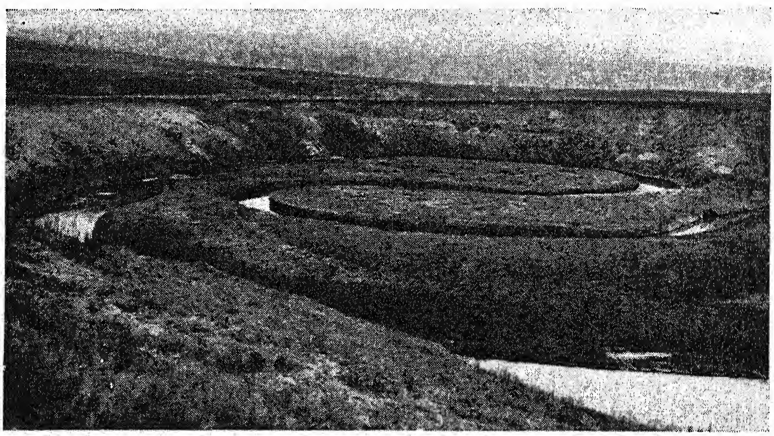


FIG. 99.—Terraces and symmetrical meanders. (*Photograph by E. B. Branson.*)

old valley. The higher terraces become the sites of cities and are much desired farm lands where the climate is humid. Where the climate is semiarid they are not as good farm land as the lower terraces, since the ground-water level is low in them and they do not have the moisture of the lower lands. Wide terraces are well developed along the Rio Grande in New Mexico, the Missouri in its course through Montana and the Dakotas, the Connecticut, the Nile, and many other streams.

Oxbow Lakes.—Where streams straighten their courses by cutting across meanders the old curves are deserted by the stream but remain filled with stagnant water; these are called bayous. The ends that join the streams are soon filled with deposits and the bayous become oxbow lakes, named from their shape. Such lakes and bayous are numerous in old valleys and common in mature ones (Fig. 84B).

Isolated Hills.—Figures 84A and 84B illustrate the development of an isolated hill by stream meandering, and hills of such origin are common. If the cap rock is hard and the lower rock soft these may form buttes. Isolated hills form also through tributaries developing secondary tribu-

taries which cut back and connect with one another and leave a hill unconnected with the adjacent ridges. These are buttes in arid or semiarid regions, and probably hills of gentle slope in humid regions. The hills are not due in any sense to harder rocks, but to the accident of the stream's failure to cut this particular area to flood-plain level. Goat Island in the Niagara River between the American Falls and the Canadian Falls will become an isolated hill when the falls cut to above the island.

SOME UNUSUAL FEATURES DEVELOPED BY STREAM EROSION

The casual observer sees the unusual features of stream erosion rather than the usual, and the unusual features are important in making up

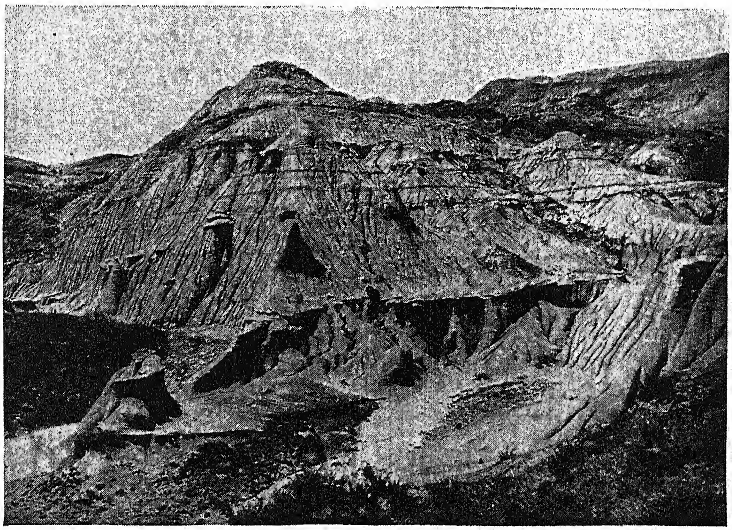


FIG. 100.—Bad Lands near Steveville, Alberta. *(From Emmons, Thiel, Stauffer, and Allison, "Geology." Courtesy of Canadian Geological Survey.)*

many landscapes. However, the unusual features of one region may constitute the usual of another.

Bad Lands.—The so-called bad lands attract the attention of everyone who crosses them, and they are normal features of stream erosion where conditions are rather peculiar. They constitute a type of mature topography with narrow, steep-sided valleys and narrow-crested hills, the entire region dissected by closely spaced valleys. The rocks making up most bad lands are alternating shales and sandstones with shales predominating, as shown in Fig. 100. They develop in arid or semiarid regions where the rainfall comes mainly in heavy showers. Figure 112 is a type of bad land with slopes much gentler than the normal bad lands. The slopes are gentler because there are no hard sandstone layers to hold

them up. In humid regions weathering and slope wash reduce all slopes too rapidly for typical bad-land development.

In some regions the rocks making up the bad lands are highly colored, and color attracts attention to them. In the Painted Desert of Arizona bands of red, green, yellow, and blue set off the picturesqueness of the rough topography. This is one of the most accessible and beautiful of the bad-land regions of the United States, and it covers an area of several thousand square miles. The Sante Fe Trail passes through it, and the road from the Sante Fe Trail to the bridge across the Colorado River at Lee's Ferry runs through it for 30 or 40 miles.

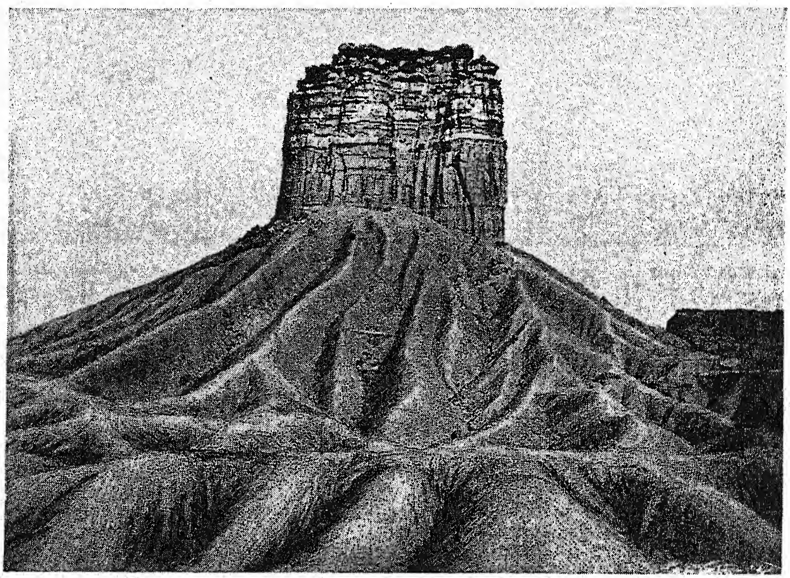


FIG. 101.—A butte in southwestern Colorado. (*Photograph by E. B. Branson.*)

Small areas of bad lands occur in almost all of the Rocky Mountain states, not in the mountains themselves but in the plateaus adjoining the mountains. The best-known are in South Dakota, Nebraska, Wyoming, Montana adjoining the Black Hills region, and Arizona.

Fossils in Bad Lands.—Many large fossils of peculiar animals have been found in the bad lands of South Dakota, and great fossil forests occur in the Painted Desert of Arizona. Some people associate large fossils with bad-land topography, but in many bad lands no fossils are known; the presence of fossils in an area is an accident of geographic and geologic location rather than a necessary association.

Buttes and Mesas.—In the bad lands are numerous flat-topped, steep-sided, isolated hills that are capped with resistant horizontal beds. Such hills are called *buttes* and are not only features of bad-land topography but are rather common in many other regions. The term "butte" is somewhat regional in its application. It is used much more

in western United States than in eastern, not only because that topographic feature is much more numerous but also because in the west it is the custom to call any steep-sided, flat-topped hill of a diameter less than a mile or two a butte, as it is also the custom to call such a hill several miles across a *mesa*. The terms butte and mesa are not used with complete distinction either outside of geological literature or in. Enchanted Mesa in New Mexico is only about 1,000 feet across the top. The mesas owe their existence to the same conditions as buttes: a hard, nearly horizontal bed of rock capping softer rock, and an arid or semiarid region in which weathering and slope wash are slow. The butte and mesa regions of the United States extend from western Kansas, Nebraska, and Oklahoma to about the Sierra Nevada Mountains with none or few present in the mountains.

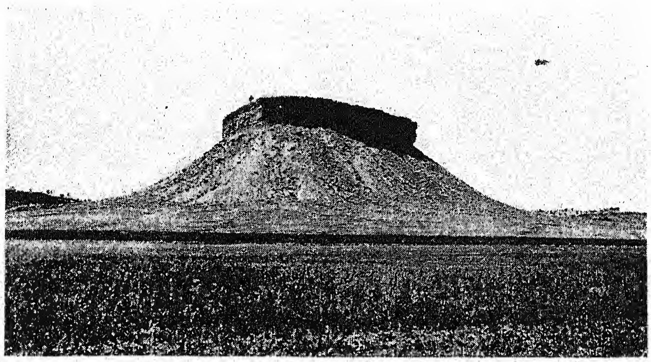


Fig. 102.—A butte capped by horizontal sandstone beds with shale beds below. (*Photograph by Willis T. Lee. Courtesy of U. S. Geol. Survey.*)

Canyons.—Canyons are features that have become sites of national parks and objects of excursions by millions of people. They are present in the main in the regions where buttes and mesas occur. The Grand Canyon of the Colorado, the most famous canyon in the world, is bounded on both sides by mesas, and buttes are numerous on its margins. Canyons may be defined as unusually deep, narrow, steep-sided valleys. Again, as with the terms butte and mesa, the term canyon is somewhat colloquial. In western United States most valleys are canyons to the inhabitants, while in eastern United States the term is not used. Niagara Gorge is as truly a canyon as the canyon of the Yellowstone in Yellowstone Park. It is neither as deep nor as narrow, but is very steep-sided and fits our definition of canyon.

In the main canyons are developed in nearly horizontal sedimentary rocks, are steep-sided because of slow weathering and slope wash, are narrow because the streams in them are very swift, and are deep because the regions in which they are cut are high. One might object that Niagara Gorge is in a region where weathering and slope wash are

important, but one condition that produces a canyon—the very swift, powerful stream—is so dominating in the case of the Niagara River below the falls that it has outstripped the agents that reduce the side slope. The gorge of the Columbia River is a real canyon, not in an arid region, but it too has been cut by a very swift, large stream through basalt, a rock that weathers rather slowly. One who visits the Grand Canyon in Arizona, the canyon of the Yellowstone in Yellowstone Park, the canyon of the Snake River in Idaho, or Zion Canyon in Utah, will be impressed by the wearing power of the streams that have produced them and by the steepness of the walls bounding them. Short canyons are

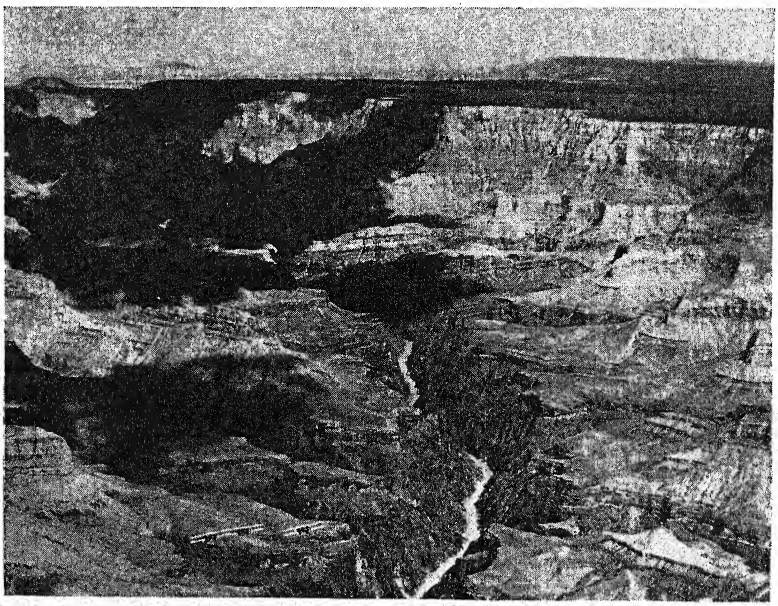


Fig. 103.—The Grand Canyon of the Colorado River; buttes in the foreground, a mesa in the background. (*Official photograph, U. S. Army Air Corps.*)

striking features of the flanks of mountains, and many of the scenic highways of western United States pass through them. Some canyons cut clear through mountain ranges, so that one may traverse the entire range without going either up or down to any great degree.

The Grand Canyon of the Colorado River in Arizona, as stated, is the most famous canyon in the world. It is by no means the deepest valley or the deepest canyon, but by combining depth, steep-sidedness, and length it excels all others. The very deep part of the canyon is about 100 miles long. Its maximum depth is about a mile, and its normal width at the top 6 to 10 miles. However, it gives the impression of much greater proportional depth because of many steep faces in the walls. The horizontal rocks making up its sides are highly colored, and

the colors of the beds are different; this emphasizes steepness. The Red Wall, for instance, is some 500 feet high in many places, nearly vertical, and in color a dull red. This extends for a great many miles along the canyon wall. Above the Red Wall is a buff rock and below are yellow, green, and brown. In places along the canyon there are sheer drops of 2,000 to 3,000 feet. The onlooker is impressed with the steepness, ruggedness, and harshness of the canyon outlook.

If one listens to the comments of the visitors to the canyon he hears the question raised, "How did the canyon form?" Only rarely does he

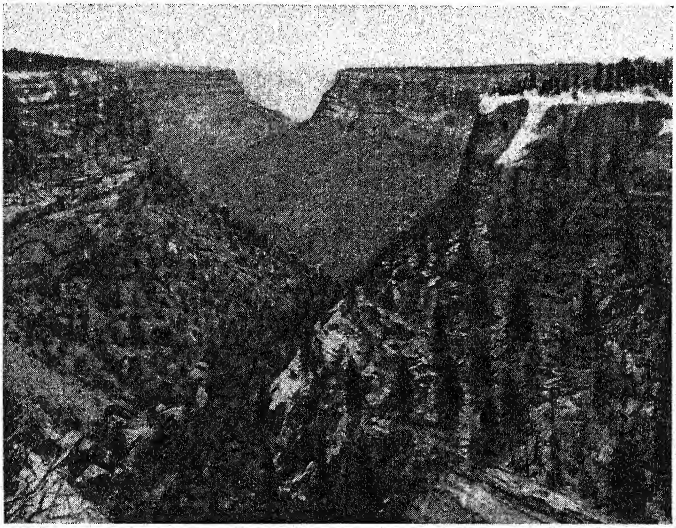


FIG. 104.—Canyon in Mesa Verde National Park in southwestern Colorado. *(Photograph by E. B. Branson.)*

hear an answer that is in any way adequate. Possibly the old Indian legend that Ye, their most powerful god, dragged something along there and thus created the canyon is as adequate as the guesses of the ordinary tourist. By determining the amount of sediments carried and the amount of water that flows through the canyon, one may find that it has not taken much longer for the Colorado River to form the Grand Canyon than for the Mississippi River to form the valley in which it flows. It has no doubt taken millions of years, but that is a short time in geologic history.

Natural Bridges.—Natural bridges originating in any way are rare, and those developed by streams are much rarer than those developed by the work of ground water. The largest natural bridges in the United States are in southern Utah, and they were developed in part by stream erosion. Two canyons were very close together, and the stream of one, undercutting at the bottom of a 200- or 300-foot cliff,

undermined it and cut through into the next canyon, leaving a rock arch above. This is a simple way but is not very common, because canyons only rarely approach one another close enough to allow the undercutting from one to reach the other. In Arizona and New Mexico,

Fig. 105.—Rainbow Natural Bridge, southern Utah. (*From Emmons, Thiel, Stauffer, and Allison, "Geology." Courtesy of Santa Fe Railway.*)

near the Utah natural bridges, are many others that are little known because the region is inaccessible. The bridges are cut in red sandstone and make very striking topographic features.

Hogbacks.—The so-called *hogbacks* are features developed where rocks are tilted and hard beds alternate with soft. Stream erosion cuts

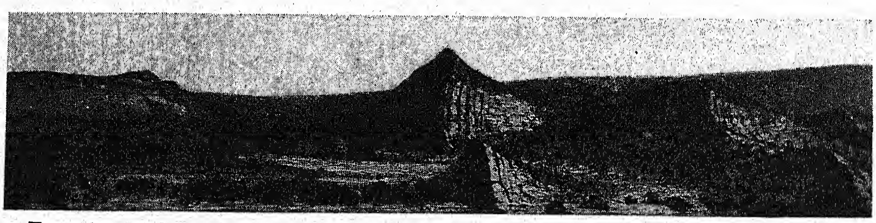


Fig. 106.—A hogback in northwestern New Mexico. (*Photograph by E. B. Branson.*)

away the softer rocks above the harder, and forms a rather sharp-crested ridge, as shown in Fig. 106. On the one side of the ridge is the face of the tilted rock and the other side is a slope formed by the softer rock that is protected by the hard. Hogbacks are common along the flanks of all mountains formed of tilted sedimentary rocks. They develop in moist climates as well as in arid, but are somewhat sharper and more clear-cut in arid regions owing to their not being covered by forests and to slow weathering.

Pinnacles and Pedestal Rocks.—In arid and semiarid regions slender spires and masses of rock perched on slender pedestals are not uncommon. The spires represent remnants of rock where surrounding rocks have

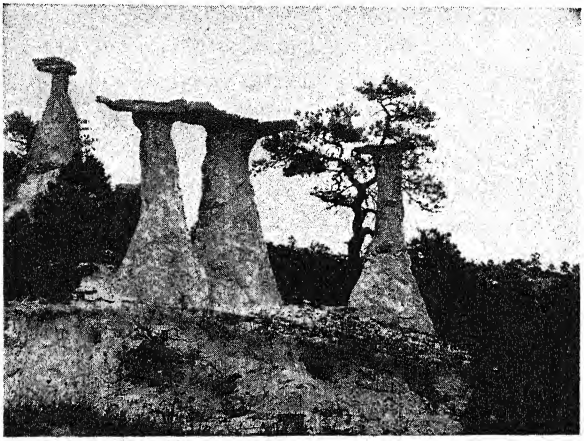


FIG. 107.—Erosion remnants in Colorado. (*Photograph by I. A. Keyte.*)

been worn away. Figure 107 is a group of spires about 30 feet high. They were isolated by stream work but have been smoothed by wind work. Figure 415 is an erosion remnant from western Kansas chalk. The total mass remotely resembles the Sphinx of Egypt, but it is much larger. Bryce Canyon in southern Utah has more pinnacles than any other area of equal size in North America. One can see thousands of them at one glance. As they are highly colored with bright shades, they make a very striking and picturesque landscape. They were not formed by stream erosion alone, but by stream erosion and ground water seeping out from near the bottom of the valleys and undermining the overlying rocks. The materials forming the pinnacles are soft sandstones and shales.

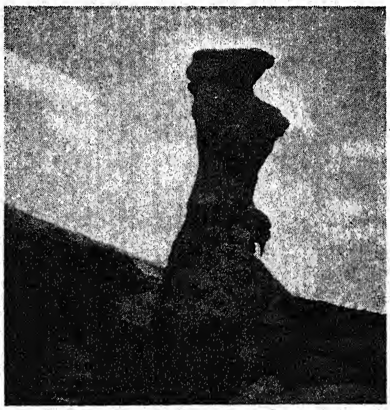


FIG. 108.—An erosion remnant in eastern Arizona. (*Photograph by E. B. Branson.*)

Rejuvenated Streams and Intrenched Meanders.—Some streams in mature and old valleys have had their velocities increased by the uplift of the land over which they flowed or the lowering of the water level at their mouths. Such streams are said to be rejuvenated, as the increased velocities cause them to cut downward in proportion to sideward much faster than before uplift took place. They create narrow valleys with meandering courses within the old valleys.

The San Juan Valley in southern Utah is an example, with large, closely spaced meanders in a narrow valley more than a thousand feet deep. The course of the stream is such as develops only on wide flood

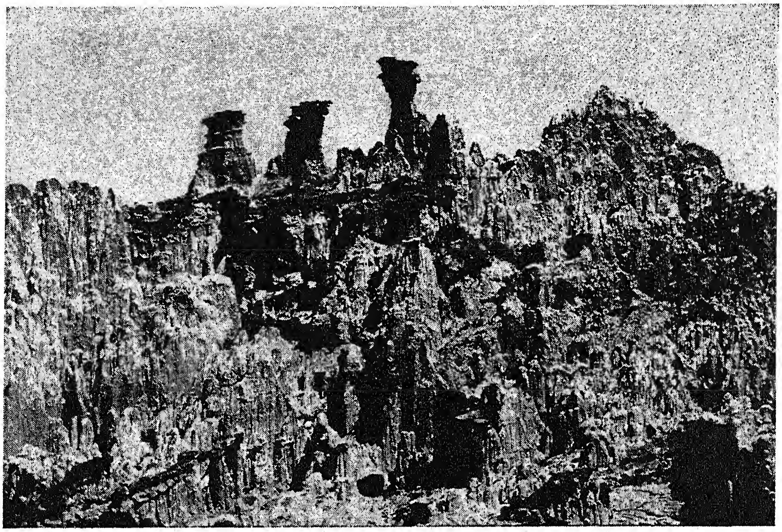


FIG. 109.—Spires in Hell's Half Acre, central Wyoming. (*Photograph by Willis T. Lee. Courtesy of U. S. Geol. Survey.*)

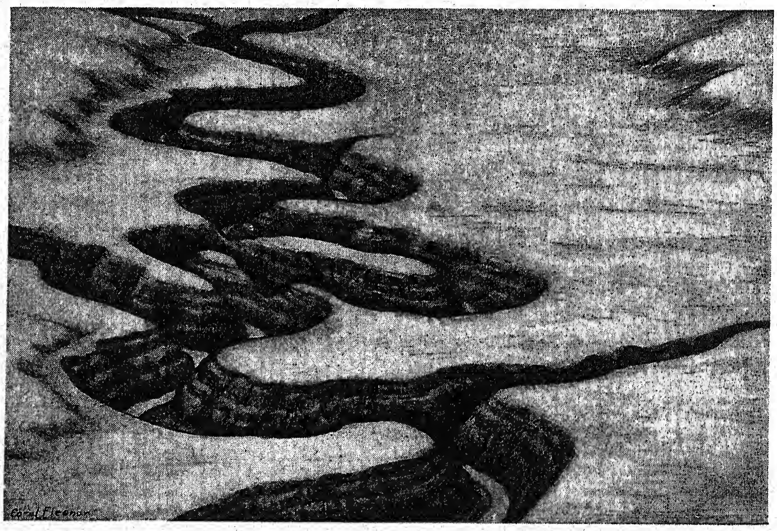


FIG. 110.—Intrenched meanders of the San Juan River of southern Utah. Drawn from maps and photographs. Depth of valley about 1,000 feet.

plains while the depth and width of the valley are such as are developed by a very swift stream. To explain the valley it seems necessary to combine both qualities, and this may be done by assuming that the stream developed a broad valley and had its grade increased. Suppose

that the Colorado, into which the San Juan empties, lowered its bed 1,000 feet at a rapid rate. The San Juan would have its grade increased 1,000 feet in the lower part of its course, and this would give it a rapid current. The swifter stream would begin to cut more rapidly at the bottom and deepen the valley without cutting laterally enough to widen it noticeably. The stream could not leave its meandering course and so deepened the valley in the old series of curves.

It should not be understood that rejuvenated streams cut straight down. Even in the most pronounced of the intrenched meanders the stream has cut laterally more than downward. San Juan Valley, given as such a striking example, is several times as wide as deep, although it appears deeper than wide.

FIG. 111.—A drawing representing the authors' conception of the San Juan Valley before intrenching took place. Note that the valley at the left in Fig. 111 becomes the valley of Fig. 110 on being intrenched.

The most common thing that starts rejuvenation of streams is the uplift of an entire region, with consequent increases in the grade of the streams from the uplifted part to another region that is not uplifted. Suppose that the part of the Mississippi River north of St. Louis should be uplifted 500 feet and the part below St. Louis not uplifted at all. This does not mean an abrupt break, but an uplift that gives a difference of 500 feet in many miles. The upper part of the river would immediately start to cut its valley down to the level of the lower part and would intrench its meanders in their courses.

AGES AND KINDS OF TOPOGRAPHIES

The shape of the land surface is called topography. Topographies are developed by various agents. Man levels an area to make a tennis court or a landing field, or roughens an area by digging ditches in it, but he has had little to do with the surface features of most of the earth.

Streams have been the most important agents in shaping earth topographies. We have considered the development of stream valleys,

and stream-developed topographies consist of stream valleys and the intervening divides.

Young Topography.—A newly uplifted sea bottom would form an ideal *young topography*—a flat or gently sloping surface. However, the newly uplifted sea bottom is likely to have valleys of large streams crossing it, and the areas between the streams are the most ideally young. As no large area exists without some sort of valley in it, most

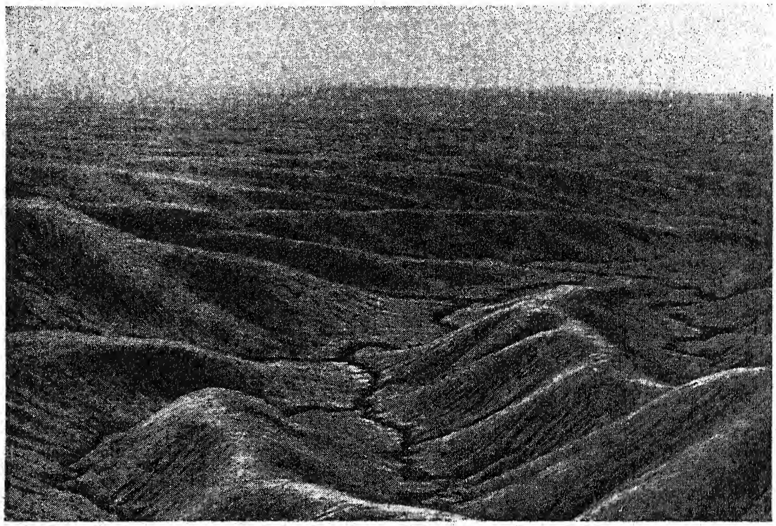


Fig. 112.—Mature topography in southwestern Colorado. (*Photograph by E. B. Branson.*)

young topographies consist of broad flat or gently sloping uplands between streams (Fig. 94). Young topography grades into mature when only small remnants of the original upland remain.

Mature Topography.—With the progress of time more and more stream tributaries establish themselves, form valleys, and change all the land to slopes toward the streams. This is the stage of full maturity, and the region is all slopes, excepting in the wide valleys. Most mountainous regions are mature and so are bad-land regions. Figure 112 is ideally mature.

Old Topography.—The mature stage continues to early old age, when most of the slopes become gentle. The region has passed from a nearly level stage (youth), through a stage where it is nearly all slopes and the slopes are steep, to a stage where it is all slopes and flats, but the slopes are gentle. The streams have cut laterally until the divides between them are inconspicuous.

Relation of Topographies to Industries.—Young topographies and old topographies may be ideal farming land, while mature topographies, particularly where the hills are high, are used mainly for grazing and timber growing. Mining is probably more common in mature topo-

graphy than in either young or old, but that is because mining is associated most commonly with mountains and not because the topography itself has anything to do with it.

Relation of Valley Age to Topographic Age.—The age of stream valleys does not necessarily have anything to do with the age of topographies. Most of the stream valleys in mature topography are young, but young topographies may have mature valleys. Mature topographies

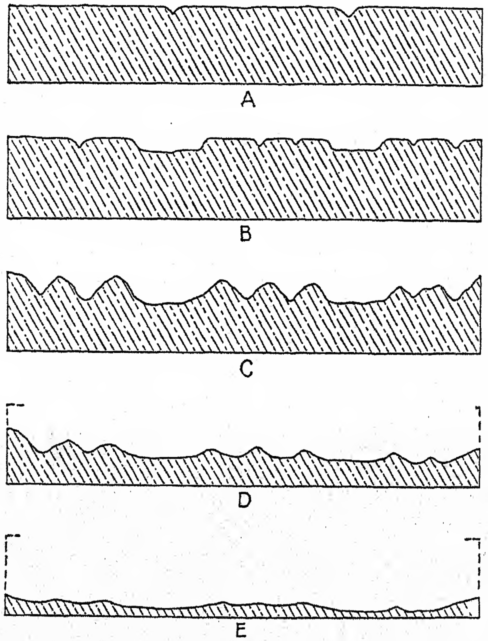


FIG. 113.—Cross-section of (*A*) very young topography, (*B*) mid-youthful topography, (*C*) mature topography, (*D*) topography in late maturity, (*E*) old-age topography. Vertical scale greatly exaggerated in all figures.

and old topographies always have some young valleys. Old topographies have streams with very wide flats, and one of the main streams shifting its course may cause a tributary stream to cut across a wide flat, creating a young valley in that flat. The age of the valleys and the age of the topographies may not be more definitely related than the age of a house with the age of its newly shingled roof.

It should be clear that there is no sharp gradation between young, mature, and old topographies, any more than there is sharp boundary between the youth and maturity of an individual or between maturity and old age. The age of topography discussed is strictly in terms of stream erosion, and other types of topographic development may so completely change the surface as to destroy the evidence of the age. For instance, a glacier passing over a region may change it from a mature stage back to a youthful stage.

Peneplain.—A peneplain is a region that has been eroded to very gentle slopes by streams. It may still have isolated hills projecting above it, hills that are either harder rock or accidental features that streams have failed to wear down. Peneplains are made up of valley flats and the gently sloping uplands between them. Part of the work of leveling the region has been accomplished by wearing and part by filling.

Base Level.—A peneplain that has been eroded to about sea level is called a base level. Streams cannot erode a region to sea level, but only to such gentle slopes that the water will run off without doing further work of cutting or carrying. A true base level, then, is an ideal thing rather than one ever attained, but geologists speak of a very low, almost level region produced by stream erosion as a base level. Base level is not created by just one stream but by a number of streams. One stream valley in a topography might be as low as the base level, but by definition the term base level applies only to regions and not to single stream valleys.

Cycle of Erosion.—Where a peneplain or base-leveled region has been uplifted and the streams rejuvenated, the narrow, steep-sided valleys that result give the topography the appearance of youth, and the region is said to have entered a second cycle of erosion. By cycle of erosion the geologist means the things that take place from the starting of erosion on a newly emergent surface to a new uplift of that region. A complete cycle would consist of the emergence of a sea bottom, cutting of that by streams through youth and maturity to base level, and then the uplift. If uplift comes before the base-leveling of the region the cycle is said to be incomplete. In the Appalachian Mountain region three periods of rejuvenation or uplift and four cycles of erosion may be recognized by erosion features. Figure 113 shows five stages in a cycle of erosion.

STREAM DEPOSITS

Checking of Velocity.—The amount of sediment that running water can move is directly dependent upon its velocity and volume. If a loaded stream, one carrying all the sand and clay that it can, has its velocity checked abruptly, the materials it is carrying are deposited rapidly. The carrying power of a stream, so far as size of particles is concerned, varies as the sixth power of the velocity. A stream that has been carrying a pebble that weighs 1 ounce, upon having its velocity checked one-half, can carry a pebble that will weigh $\frac{1}{64}$ ounce. It is not strange then that most stream deposits are formed on account of the checking of the velocity of the water.

Decrease in Volume.—Deposits made on account of decrease in volume are conspicuous where streams flow from moist to dry regions and

evaporation and soak-in take up much of the volume of the stream. The Platte River in Nebraska is an example. Many of its tributaries, as they come from the Rocky Mountains, carry more water than the Platte itself after it reaches the plains. The volume of the river has been reduced and the river actually fills its own channel with deposits so that there is not room for its waters. The result is what is known as a braided stream.

Many streams of the Rocky Mountain region have their waters diverted for irrigation purposes, and on that account they are unable to

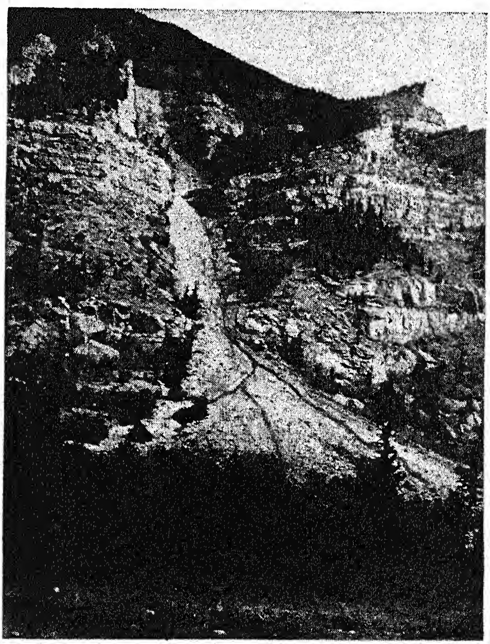


FIG. 114.—A steep alluvial fan on North Fork of Popo Agie River, Wyoming. (*Photograph by E. B. Branson.*)

carry the sediments present before the water goes into the ditches. The same volume of water is present, but it comes in contact with much more surface than while it was in the main stream. The carrying power of a stream depends in part on its volume, but a deep, narrow stream can carry much more than a wide, shallow one of the same volume, as it comes in contact with much less rock surface.

Alluvial Fans.—Where a stream comes from a relatively high grade to a much gentler slope, as from mountains to plains, its velocity is checked quickly and for that reason it builds up alluvial deposits. These deposits are formed so rapidly that there is little sorting of the materials, and as they are deposited on land there is no later sorting. The deposit consists of all the materials, big and little, carried by the stream, piled up in a heterogeneous mass. Such a deposit spreads out from the steep

slope in the shape of a fan and is known as an *alluvial fan*. As the fan grows outward by addition at the outer margins, the grade ceases to be steep, the materials are not deposited so rapidly, are finer, and are better sorted.

The stream builds the fan by overflowing its channel. The largest deposits form where the water first leaves the channel, and the margins of the stream channels are the highest part. Where the stream channel becomes so high as to be out of harmony with the rest, the stream breaks through and takes the lowest course over the fan. It repeats many times the process of filling and escaping from its high channel.

Fans at the base of high mountains may grow until they extend hundreds of miles from the mountains. They grow laterally to join other fans, forming compound alluvial fans. East of the Andes in Argentina

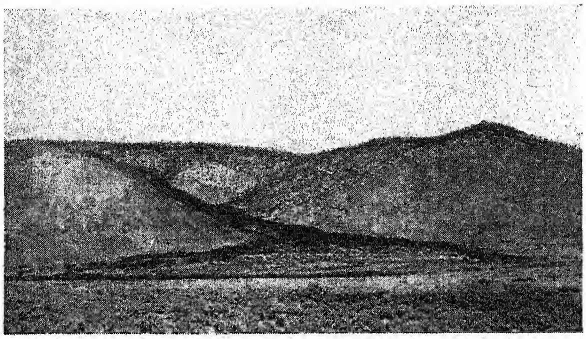


FIG. 115.—A small alluvial fan. (*Photograph by E. B. Branson.*)

the entire slope nearly to the sea is made up of alluvial fans. East of the Rockies in Colorado fans spread far out into Kansas. In western California the large orange orchards are largely on alluvial fans.

Flood-plain Deposits.—Flood-plain deposits are formed by streams and are present in all valleys that have developed flats. In the main they form from deposits on the inside of meanders, but in part are direct deposits from floods that spread from the river channel over the flood plain. Normally the deposits range up to 40 or 50 feet thick but in some places are much thicker, and they occupy the entire width of valley bottoms, save where the stream cuts through them to the solid rock.

In old topography flood-plain deposits may form nearly half of the surface of a region, although in early old age they probably do not form more than one-tenth and in young stages they are of small area. Flood-plain deposits are in the main composed of clay and sand, but as the river gets rocks of various kinds and sizes from the valley sides, gravels are by no means uncommon and boulders occur in some places. One might follow up the course of the Mississippi-Missouri River and its

tributaries to near the top of the Rocky Mountains and everywhere find flood-plain deposits. The deposits in the flood-plains of the Missouri's branches, coming from the Rockies, are different in composition from the materials in flood-plains deposited near its mouth. Those of the mountain stream are made of larger fragments than those that are deposited by streams far away from the mountains, and the tributaries coming from flat regions bring different materials than streams from the mountains.

Flood-plain deposits are among the richest of soils and are the most intensively tilled of all soils, particularly in semiarid regions where they have the advantage of getting more moisture than the upland soils.

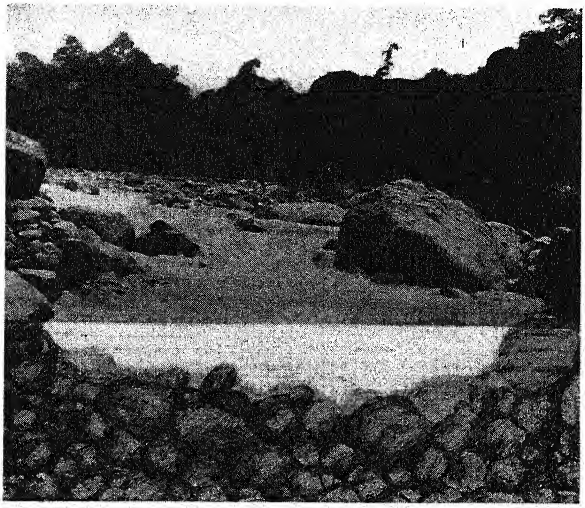


FIG. 116.—Deposits in the flood-plain of a swift stream in Costa Rica. A section of the stream and deposits drawn in the foreground. (*Photograph by E. B. Branson.*)

In Kansas, Nebraska, and other states of similar climate the bottom lands, flood-plains, may produce large crops while the uplands produce very little. In some places farmers are finding greatest profit in cropping the flood plains and grazing the uplands, and farms with both upland and valley parts prove most profitable.

Control of River Building.—The danger of floods on some flood-plains constitutes the hazard of farming them. Scientific planning of the handling of side streams may entirely eliminate flood-plain dangers from some areas. Near Kinderhook, Illinois, a farmer purchased a rather large farm, most of which was flooded every year and part of which was oxbow lakes and swamps. The land was worth about $30 an acre. The custom in this region was to build levees to keep water off the farms. This farmer found that the water got into the fields in spite of the levees, and he evolved a new plan for his farm improvement. He built a levee

around one field to hold the flood water in and retained it until all the clay and sand had settled. With water 2 feet deep over the field, clay and sand might settle out from one flood to a depth of 3 or 4 inches. By treating the land in this way for 16 or 17 years he built his entire farm up some 3 or 4 feet, and the old oxbows and swamps were filled to the level of the rest of the farm. With his farm 3 or 4 feet above the surrounding land he was in no danger from floods, and some of his neighbors actually bought right of way through his property to let the flood waters come through and build up their farms. The value of the land changed from about $30 an acre to $250 an acre.

Natural Levees.—All large rivers in mature and old valleys overflow their main channels at times of great floods and deposit and cut away materials from their flood-plains. As flood water fills the main channel and overflows laterally it makes deposits on the immediate banks

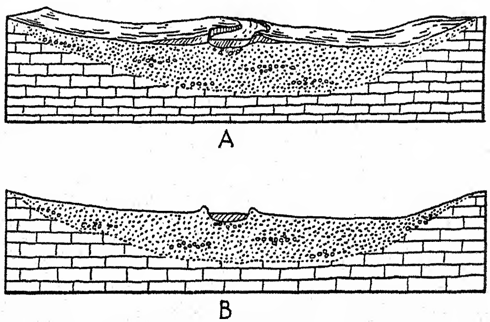


FIG. 117.—(*A*) Natural levee; (*B*) artificial levee.

of the river course where the velocity of the water is checked by shallowing. In course of time the deposits on the bank build up above the rest of the flood-plain and form a distinct topographic feature known as a natural levee. In large rivers natural levees may be several feet above the general level of the flood-plain of the river, but they are inconspicuous on account of their very low slope away from the river, and they are most easily observed in flood time when the flood-plain of the valley is covered with water save for the narrow strip along the immediate bank of the river. The river itself acts as a check on the height of the levee. If it builds a little too high, the river breaks through in flood time and does not return to its old channel. In the main the levees help the river to keep its channel in times of high water; but the materials are loose clay and sand, and the river may overflow, cut through the levee, and spread over the flood-plains beyond. Nearly all streams with large natural levees are subject to disastrous floods.

Rivers with high natural levees and great plains in their lower courses may change their courses very greatly in flood time. The Hwang Ho River flowed into the Yellow Sea previous to 1853, when it broke through

its levee took a new course and emptied into the Gulf of Pohai 200 miles north of its former mouth. All efforts to turn it back were unsuccessful and it started at once to build a delta at its new mouth.

The Mississippi River had many mouths which opened into the Gulf, and these filled up with sand and clay so as to make navigation uncertain. An engineer, James Eads, planned jetties that should be just wide and deep enough to have the river current sweep them clear of sediment. They were finished in 1879 and no trouble has been experienced with navigation of the lower delta since that time. This is an example of the application of science to the control of natural forces. Dredging out a channel would have been easier and faster, but the dredging would have had to be kept up all the time, would have cost more finally than the jetties, and would have been less satisfactory.

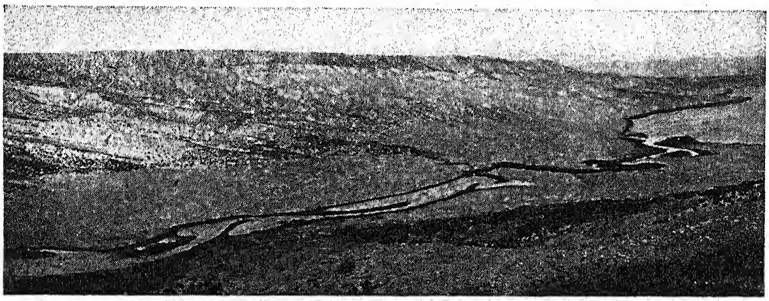


FIG. 118.—Levees in time of flood. The levees are marked by the belts of vegetation with water on both sides. The water is high enough to cover the flood-plain near the river except the levees. The levees are only about 2 feet high and are not continuous as the meandering of the stream has removed them in some places. (*Photograph by E. B. Branson.*)

All rivers with flood-plains of considerable width have natural levees, but they are inconspicuous and unimportant along small rivers. Even mountain streams have natural levees. Figure 118 illustrates a mountain stream in flood time with the tops of the natural levees showing above water near the main stream.

Artificial Levees.—Natural levees are made of materials which form rich soils and in spite of the danger of floods are densely inhabited along some rivers. The inhabitants, desiring to prevent damage by floods, build artificial levees on the natural. Such levees extend along the Mississippi River on both sides from New Orleans northward to north of St. Louis. As artificial levees are thin, they are weaker than natural levees, are more easily broken by floods, and the floods are so much more destructive. Along the Hwang Ho River in China the artificial levees are built up 10 to 25 feet, and when the river breaks through it means disaster to the inhabitants of the valley. The river is known as China's sorrow owing to the number of people it has destroyed. The great floods of the Mississippi River are associated with the breaking of the

levees, and one of the big problems of the national government is flood control of the Mississippi and its tributaries.

Effects of Floods.—Control of floods cannot be accomplished by building levees but must go back to the source of flood waters and control them to some degree. The source of floods in the plains regions of the United States is rainfall, in the mountain regions mainly melting snow. If heavy rains on the plains coincide with the high-water stages from melting snow, the greatest floods result.

Deltas.—It has been determined that the Mississippi River carries enough sand and clay in suspension every year to make a deposit 268 feet

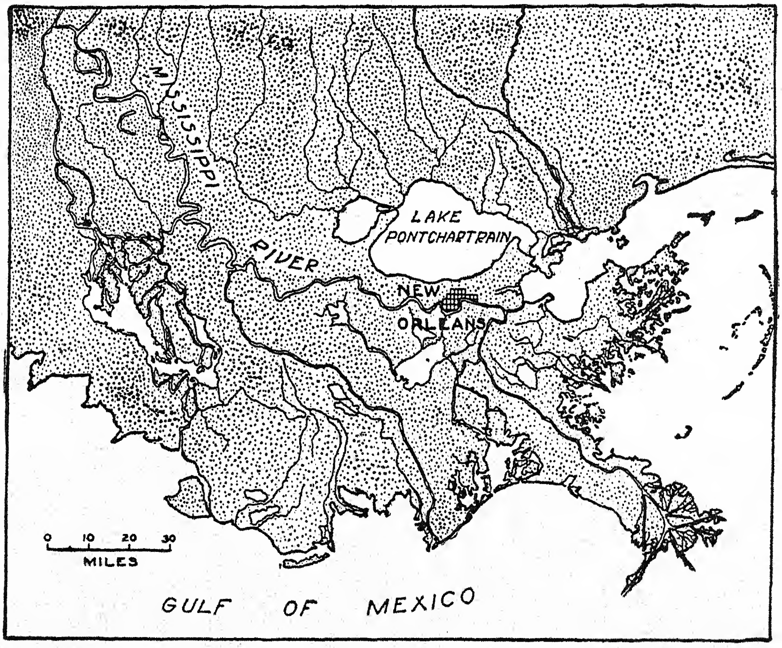


FIG. 119.—A map of the Mississippi Delta. (*After Emmons, Thiel, Stauffer, and Allison, "Geology."*)

deep over 1 square mile. That amount is actually carried through the mouth of the Mississippi into the Gulf, and most of it is deposited in the *delta* near the mouth. (The volume was determined by sampling the waters of the Mississippi every day of the year for many years and determining from the samples the amount of sediments carried.) As soon as the water of the Mississippi strikes the relatively stationary ocean level it deposits most of the load that it has been carrying. Material as coarse as fine sand goes to the bottom within a mile or two of shore. Clays will stay in suspension for several days and may be carried hundreds of miles into the Gulf before settling to the bottom.

The sands which are deposited at the immediate mouth of the river gradually encroach on the sea by filling up the shallow parts, and cause

the delta to grow seaward. They grade imperceptibly into finer sediments farther out. At times of flood muddy waters stand over the part of the delta that has been built to sea level, and sediments deposited from these waters gradually build the delta above sea level. The amount of material in a delta will depend upon the amount carried by the stream and the length of time the stream has been working. In 100,000 years the Mississippi would carry enough materials to make deposits 268 feet deep over 100,000 square miles, 26.8 feet deep over 1,000,000 square miles. Such deposits would be almost entirely made up of clay and sand, and most of the clay and sand would have resulted from complete chemical weathering; the sand would be mainly made up of quartz grains and the clay of various clay minerals.

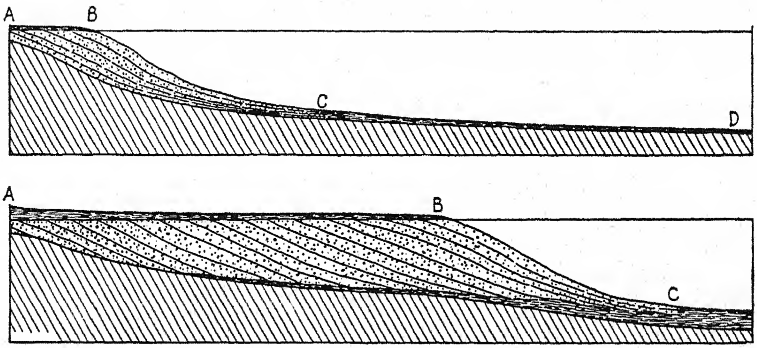


FIG. 120.—Upper figure, a young delta with bottomset beds (*C-D*) of large extent. Lower figure, a longitudinal section of a delta with foreset (*B-C*) and topset (*A-B*) beds of large extent.

The building of the delta of the Mississippi probably started about southeastern Missouri and progressed outward to its present location, some 600 miles south. The first deposits were made in the head of a narrow bay, but the bay filled and the near-shore deposits widened until they extend from Louisiana almost to central Texas. More than 200,000 square miles have been filled by the Mississippi to depths ranging from something over 100 feet to several thousand feet, and the river has probably been working several millions of years to make the deposits. In making such a deposit the stream must have changed its course thousands of times, at times flowing near the eastern margin of the delta, at other times near the western margin, and occupying all intermediate places many times.

As a delta starts there is no part above water, and the submerged part continues to be very much larger than the part above water through the earlier stages of delta growth. If the sea is very shallow, a large stream may fill the shallow part rather rapidly and the landward part of the delta will grow in proportion. The 200,000 square miles of landward part of the Mississippi delta was once all suboceanic, so that in

drilling wells through the delta sediments most of the materials encountered were deposited below the sea. This is determined by fragments of sea shells found in the well cuttings.

Seaward there is no sharp line of demarcation between delta deposits and the normal sea deposits. The very finest of the clay brought in by streams is widely diffused through the ocean waters and may settle to the bottom at places remote from the delta. Sediments direct from Amazon River waters are carried out and deposited some 700 miles from the mouth of the river, but it is only very large rivers with strong currents that carry materials far out. All of the deposits from a distance of 20 or 30 miles out from shore are clay, unless the ocean is so shallow that storm waves strike the bottom.

We may picture a young delta as with a subaqueous part made of clays, covering a large area; a very shallow-water part made up mainly of sands, covering a small area; and the part above water very small.

As the delta grows, the subaqueous part and shallow-water part remain much the same size, but the part above water increases and in late stages becomes the largest part. In drilling wells for oil or water in the Mississippi delta, the drill cuts through a few feet to possibly 100 feet of sand and clay deposited above the ocean level. Below this are found a few feet deposited in shallow water, and below that a few feet to possibly a thousand feet or more of clay with some fine sand, deposited far from shore.

Rivers emptying into seas with strong tides or very strong wave action deposit sediments in the same way as others, but the waves and currents sweep them away and deltas do not form. Small deltas may form where tributary rivers empty into larger rivers with weak currents. Deltas forming in lakes may completely fill the lakes.

Deltas have been important places in human development. The Nile delta is famous for its early civilization. The delta of the Tigris and Euphrates was one of the early sites of man's development. The delta of the Hwang Ho has one of the densest populations in the world and one of the oldest. The delta of the Mississippi saw a few of the oldest settlements in America and supports some of its important cities.

Streams like the Mississippi carry several times the volume of sediments that they deliver to the Gulf, but the materials that are deposited in alluvial fans and flood plains do not actually reduce the general level of the land; the only materials lost to the continent are those carried away and deposited in the seas. Not only that, but before a region has reached base level all the materials of its higher alluvial-fan and flood-plain deposits are removed, carried to the sea, and deposited.

Summary of Stream Deposition.—Most streams carry clay and sand, and very swift streams carry and roll coarser materials. Most stream

deposits are caused by checking of velocity of the water. Stream deposits are coarsest in alluvial fans and finest in deltas. Under some conditions deltas are the main stream deposits; under others, alluvial fans; and under others, flood-plains. Alluvial deposits form some of the richest farm land. Many regions of alluvial deposit are densely populated and the inhabitants are in danger from floods.

CHAPTER VII

GROUND WATER

Ground water, as the name suggests, is water that occurs in the ground but relatively near the surface. Other names are applied to it. *Meteoric water* is a common name which refers to the fact that the ground water originated in the air. This term is useful as a contrast to *magmatic water*, the name applied to water originating in a magma. A type of ground water known as *connate water* occurs in some sandstones. This water was incorporated in the pores of the sandstones when the deposit was made on the sea floor and was then buried along with the sandstone. It has, therefore, a composition similar to that of sea water. Our discussion in this chapter will deal entirely with the water having its source in the rain and snow that fall upon the earth's surface.

Amount of Ground Water.—If the average annual rainfall for the world is regarded as 36 inches (it ranges locally from 0 to more than 500 inches), the quantity of water falling annually upon the 54,000,000 square miles of the earth's land surface is about 30,500 cubic miles. The amount of water that runs off following rains is estimated to be about 30 per cent of the total, or about 9,000 cubic miles. This is practically the volume of water that annually reaches the ocean by means of rivers, which leaves about 21,000 cubic miles of the water that falls on the land to go underground. Most of this ground water is returned to the air by evaporation from the soil and transpiration by plants. The amount so returned varies widely, depending upon differences in climate and other influencing factors. The remainder of the ground water penetrates to variable depths, but much of it eventually finds its way to the surface through springs and seeps. A small amount of ground water goes into the composition of various secondary minerals being formed, and so remains indefinitely underground. Many estimates have been made of the total amount of ground water in the rocks. One of the latest estimates, and probably the best, places the amount at a quantity that would cover the entire surface of a sphere the size of the earth to a depth of 100 feet. This volume of water underground is transient in character, for as some of it reaches the surface more rain water sinks down to take its place.

Factors Controlling the Amount of Ground Water.—The factors controlling the amount of rain water that goes underground are (1) *rate of rainfall*, (2) *slope of the surface*, (3) *amount of vegetation*, (4) *porosity*

of the surface rock, and (5) *the amount of water already in the pores of the rock.* It is readily seen that a slow rain falling on a grass-covered, gently sloping surface that covers a dry, porous soil would mean a maximum amount of water going underground. As these factors differ widely in various parts of the earth, a similar difference is found in the amount of water beneath the surface in the different places.

The Downward Penetration of Ground Water.—Water in going underground follows the joints and fissures of the rocks, and from these openings works its way into the cracks and the finest pores. The size and number of the openings in rocks differ widely; in some rocks there are many openings; in others, such as granite, there are very few. Openings are, of course, most abundant near the surface. They may extend downward for great distances, not as single, continuous openings but as more or less connected ones. It has been determined experimentally that the strongest rocks are unable to sustain an opening below a distance of 10 or 11 miles from the surface, and weaker ones do not have openings even within a mile of the surface. The zone in which cracks, joints, and fissures can exist in the rocks is called the *zone of cavities.* However, there are good reasons for believing that the maximum distance ground water penetrates below the surface is only a few thousand feet. The vast majority of deep oil and gas wells and mines show that actually most of the ground water occurs within 2,000 or 3,000 feet of the surface. Many mines of that depth are dry and dusty; in fact, many within 1,000 feet of the surface contain very little water. Water has to be pumped into most deep oil wells during the drilling. No water was found in a well 10,077 feet deep that was drilled in Oklahoma in 1931. The water occurring in these deep wells is usually salt water; hence it is probably connate water. For the most part, however, the ground water is near the surface, although special positions of the rocks permit its descension to considerable depths.

Ground-water Zones.—As we have just seen, the zone of the ground water, though it *may* correspond to the zone of cavities, usually lies near the surface. The top of the zone in which the rocks are more or less saturated with water is known as the *water level* or *water table.* The former name does not mean, however, that the top of this zone is level, for it follows, roughly, the surface of the land (Fig. 121); and it shifts with the seasons, being higher in a rainy season and lower during drouths. The water level tends to flatten and would become essentially flat if no more water were added from above.

Of this zone of ground water, the unsaturated area above the water level is known as the *vadose-water zone;* and the saturated part below the water level, as the *ground-water zone* (Fig. 122).

The *vadose-water zone* is the zone of the most rapid water circulation as the water in it is moving downward to the water level (Fig. 123).

This zone has been called[1] the *zone of aeration*, because air can be present down to the water level. As the meteoric water moves downward through this zone, it attacks the minerals and rocks along the walls of the fissures and alters them. It is aided in this by the gases in the air

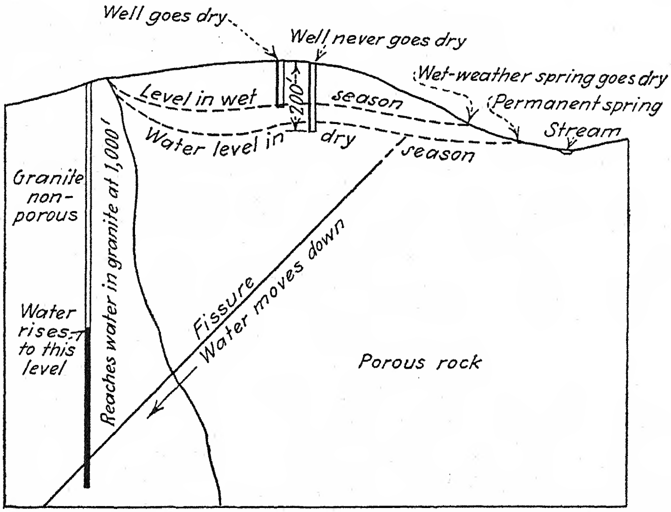


FIG. 121.—Sketch showing the various positions and relationships of the ground water to the surface.

and the acids acquired by attacking the rocks, as has been fully explained under Weathering. The vadose-water zone is the zone in which the major part of the chemical work of ground water is carried on. The greatest amount of the solvent work goes on here; for, after the water has dissolved a particle from the walls, it moves on and thus permits a fresher solution to take its place and dissolve more of the rock. In some regions the vadose-water zone contains very little water, the only amount present being that in the soil at the top, sometimes known as *soil water*. The thickness of the vadose-water zone differs with the character of the rocks and the climate.

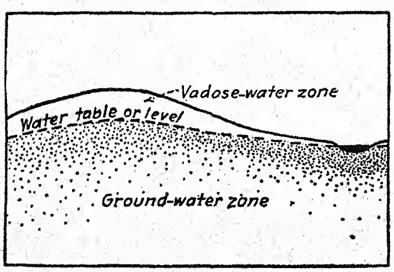


FIG 122.—Diagrammatic sketch of vadose-water zone; water level or water table; and ground water zone. Degree of saturation is indicated by density of stippling. (*From Tarr, "Introductory Economic Geology."*)

The *ground-water zone* may extend from the surface to variable distances below it. In some regions there is no ground-water zone; in others, it may lie several hundred feet below the surface. Where the ground-

[1] O. E. MEINZER, "Occurrence of Ground Water in the United States," U. S. Geol. Survey *Water Supply Paper* 489, p. 76, 1923.

water zone cuts the surface, springs and seeps are present (Fig. 121). The movement of the water in this zone is very slow, or there is no movement; hence the chemical changes are largely those of cementation and hydration. The ground-water zone is the storage place from which we obtain our water supplies.

Rate of Movement of Underground Water.—As stated, the water moves fastest in the vadose-water zone, and extremely slowly, if at all,

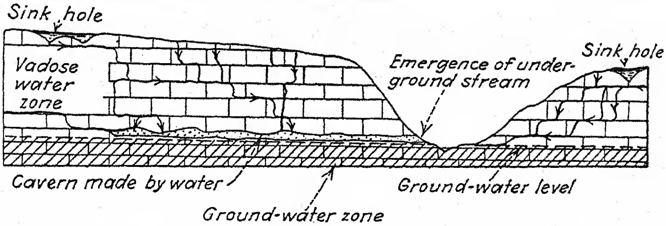


Fig. 123.—Sketch showing course of ground water in vadose-water zone, and development of sink holes and caverns.

in the ground-water zone. In some rocks, such as fissured and channeled limestones, the water flows as rapidly as it does in streams; indeed, the openings, if large, may contain underground streams (Fig. 123). In the smaller cracks and in the pores of sandstones, the increased friction greatly reduces the rate of flow of the water. Since the rate of flow is so very slow in sandstones, a supply of water obtained in a sandstone whose inflow is many miles away may not equal its removal through

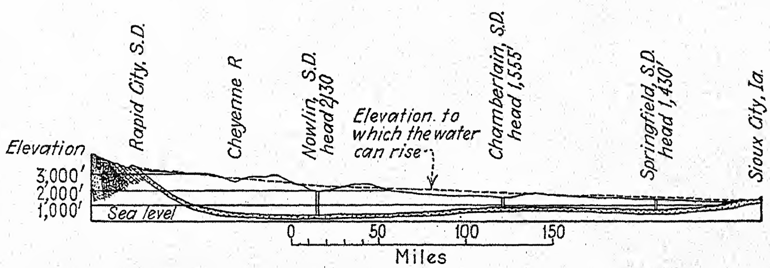


Fig. 124.—Sketch showing position of water-bearing Dakota sandstone beneath the surface, and source of its water in mountains to the west. Wherever dashed line is above the surface a well drilled at that point would have been a flowing well; wells drilled elsewhere would have been artesian but not flowing wells. (*After N. H. Darton, U. S. Geol. Survey, Water Supply Paper* 428, *p.* 31, 1918.)

the wells, whereupon the water level falls. An illustration of this is found in the Dakota sandstone, which furnishes the water in the Great Plains area and has its inflow in the Rocky Mountains (Fig. 124). Fifty years ago the deep wells to this sandstone were flowing wells. They were allowed to flow night and day, however, until the pressure was so decreased that they ceased to flow. They must now be pumped, and the water level is still falling. It is possible to determine

the rate of flow of underground water by putting a substance that can easily be detected into the water of one well and watching for its appearance in adjacent wells. By this experiment the rate has been found to be a few feet per day in certain regions.

Keeping in mind these facts regarding the volume, depth, and movement of ground water, let us now turn to a consideration of the geologic work of ground water.

HOW GROUND WATER ACCOMPLISHES ITS WORK

We have already shown that the work of the eroding agents is accomplished by *mechanical* and *chemical methods* and that each agent has its dominant method. Ground water differs from all the other agents in that its work is largely chemical. This is because it is in constant contact with the minerals of the rocks, and because water is able to bring about some chemical change whether it contains acids or is pure. Though the solutions move slowly, the unlimited time available enables them to bring about marked changes in the rocks. As the processes go on more or less continuously, a great thickness of mantle rock may be produced; enormous caverns may be formed, such as those of Mammoth Cave in Kentucky or Carlsbad Cave in New Mexico; or poor deposits of valuable metals may be converted into rich deposits, like some of the great copper deposits of western United States (see Fig. 62, page 154) or the enormous iron deposits of the Lake Superior region. The work of ground water and the process of weathering are so nearly one process that it will be impossible to draw a sharp distinction between them in our discussion.

CHEMICAL WORK OF GROUND WATER

Since the chemical work of ground water is the most important, we shall consider it first. The material carried in solution is spoken of as the *load* of the water, and the three successive steps in the work of ground water may be outlined as follows:

1. Getting a load.
   a. How?
   b. Where?
2. Transporting the load.
   a. Where?
3. Depositing the load.
   a. Why?
   b. Where?

Getting a Load.—Water begins its attack upon the minerals of the rocks as soon as it has passed beneath the surface. It dissolves any soluble material it encounters and attacks the other materials by slowly altering them into soluble and insoluble products. The insoluble prod-

ucts are left behind and form the mantle rock and soil. The nature of the soluble products removed depends upon the composition of the original rock. We have shown under Weathering that a small group of soluble products are always being removed by ground water and it is these that we shall consider here. They are, in the order of their abundance:

1. Calcium carbonate and calcium sulfate.
2. Colloidal silica.
3. Sodium carbonate, sodium sulfate, and sodium chloride.
4. Magnesium carbonate.
5. Potassium carbonate (in small amounts).

Carbonate waters, *i.e.*, those containing carbonic acid and carbonates, are the most abundant type of ground and spring waters. In order that the ground water may dissolve calcium carbonate ($CaCO_3$), additional molecules of carbon dioxide must be available. These are furnished by the carbon dioxide gas commonly present in the water. The carbon dioxide unites with water to form carbonic acid, thus: $CO_2 + H_2O = H_2CO_3$. The carbonic acid then unites with calcium carbonate to form calcium bicarbonate (which is soluble), thus: $H_2CO_3 + CaCO_3 = CaH_2(CO_3)_2$. Magnesium carbonate is dissolved by ground water in the same way. Colloidal silica is soluble in carbonate waters and is fairly common in ground water. The sulfate type of ground water is less abundant, although some sulfate is nearly always present owing to the breaking up of some sulfide minerals. Waters containing chlorine are still less common but a little chlorine may be present.

The ground water gets its load from many sources. The soil furnishes some material, but not so much as do the rocks below, because the soil consists of the residual insoluble material. The surface of the rock beneath the soil, especially if the rock is limestone or dolomite, is an important source of material. In these two rocks the contact of the residual material (mantle rock) and the original rock is sharp, which is in marked contrast to the gradational contact of an igneous rock with its soil (see Fig. 63, page 57). Within a rock the material is obtained chiefly along the walls of the joints and fissures. If the rock is soluble, the opening is widened; if it is insoluble, an altered zone is formed along the walls of the fissure or joint. In even the most minute openings some material may be obtained, but very slowly as the movement of the water there is practically negligible.

Transporting the Load.—The material taken into solution is carried along with the water as it moves through the rocks. The dominant circulation of the water is through cracks, joints, and fissures, all of which are tabular openings lying at all angles in the rocks and crossing each other at all angles. Water moves through sandstone, channeled limestone,

and tuff in any direction, but except in such a limestone (Fig. 125) the rate is slow. Water may work its way downward along one set of joints and find its way upward again along another set. In some mines, tunnels have been driven through hundreds of feet of rock that was dry, although jointed, and then a large fissure was found along which water was circulating in exceptionally large amounts.

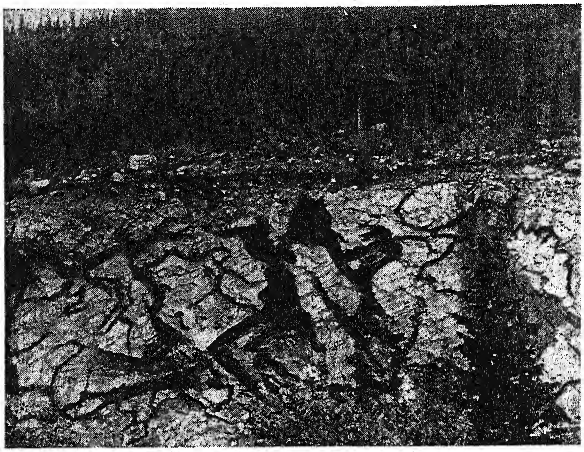


FIG. 125.—Solution channels developed along fault plane in limestone, Monarch, Colorado. (*Photograph by W. A. Tarr.*)

Depositing the Load.—The material in solution in the ground water will either be deposited in the rocks or, finally, through springs and seeps, be fed to streams and contributed to the sea. The material which enters the sea will be discussed later under the Work of the Ocean, so we shall confine our study here to that which is deposited by the ground water.

The ground water is capable of dissolving only limited amounts of mineral matter. When it has taken up all it can hold it is said to be *saturated,* and then slight changes will cause the deposition of some of the material.

Causes of Deposition.—A full discussion of the causes of deposition will not be given here, but only an enumeration of some of the simpler and more common ones.

a. The *loss of carbon dioxide* is probably one of the most common reasons for deposition, especially of the carbonate minerals. As already indicated, this carbon dioxide is a loosely combined gas and, as long as the water containing it is underground, the gas is confined and so retained, but when that water emerges at the surface the carbon dioxide escapes into the air and the carbonate is consequently deposited. Some spring waters contain so much carbon dioxide and calcium bicarbonate that deposition of calcium carbonate when they emerge is remarkably fast.

Objects such as wooden images, fruits, and bird nests are often immersed in these waters and become coated with calcium carbonate. A thin layer may be deposited in 24 hours. Large deposits of calcium carbonate are formed around such springs, as will be noted later. Boiling a carbonate water drives off the carbon dioxide and a deposit is left, such as the *scale* on the inside of a teakettle or in boiler pipes.

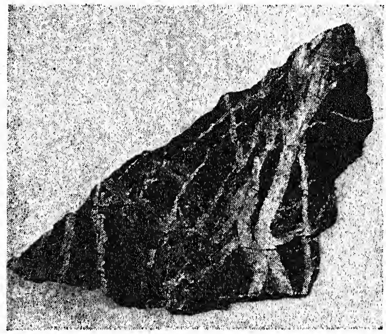


FIG. 126.—Quartz veins in gabbro. Note how veins intersect. Specimen from Maine coast.

b. The lowering of the temperature is another means of bringing about deposition, especially if the water is hot, as in the hot springs of Yellowstone Park. Hot water can hold more material in solution than cold water; hence if the hot water is saturated and the temperature falls some of this material must be deposited.

c. The *evaporation of a solution* will cause *all* the material to be deposited. Deposition by evaporation takes place in the soil near the surface during dry periods and forms a deposit known as *caliche.* Water used for irrigation purposes dissolves mineral matter from the soil and, as evaporation is rapid at the surface, redeposits it on top of the soil, often ruining it for agricultural purposes.

d. The *mingling of solutions* is a very important means of causing deposition. When waters from different sources bearing different materials in solution come together and mingle, the materials may form new compounds, some of which will undoubtedly be insoluble and thus will be deposited. This mingling may occur where two large fissures or joints cross, and the deposition of the mineral matter may finally fill up the opening at the intersection. Many different kinds of minerals, some of which are very valuable, may be formed in this way.

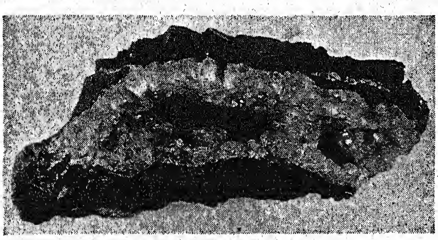


FIG. 127.—Calcite crystals in vein cutting coal. Cavity is a vug. Specimen from Boone County, Missouri. About one-fourth natural size.

e. Deposition may occur as a result of *the action of the solutions upon the walls of the cavity* in which the water is moving. By this means the wall rock is altered, *i.e.*, new minerals are formed and others are removed. These reactions involve most of the changes due to weathering.

Deposition in the Rocks.—Deposition beneath the surface takes place largely in the ground-water zone, though deposits may be formed in the vadose-water zone, also.

Undoubtedly the most common place in which deposition occurs beneath the surface is *the openings between the grains of the rocks.* The deposited material fills up the pores, acting as a cement to bind the grains together. In this way sands become firm sandstones. The material most commonly deposited is calcium carbonate (calcite); other common materials are colloidal silica, which becomes quartz, and the iron oxides hematite and limonite. Such deposition is going on so commonly that the term *zone of cementation* is frequently applied to the ground-water zone.

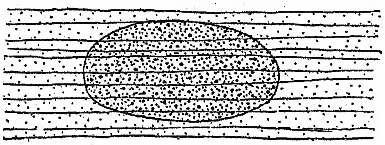


Fig. 128.—Sketch of concretion formed by cementation of local area in sandstone. Note that bedding planes pass through concretion.

Fig. 129.—Concretion (about 10 feet in diameter) of sandstone cemented with iron oxides, Fergus County, Montana. (*Photograph by W. A. Tarr.*)

The next most common place in which deposition occurs is in the *cracks, joints, and fissures of the rocks.* The deposits formed in these openings are thin, tabular deposits called *veins* (Fig. 126). When an opening is filled up, the water must find another opening or movement must cease. These veins, unlike those formed by the cooling of an igneous rock, rarely result in deposits of valuable minerals or metals.

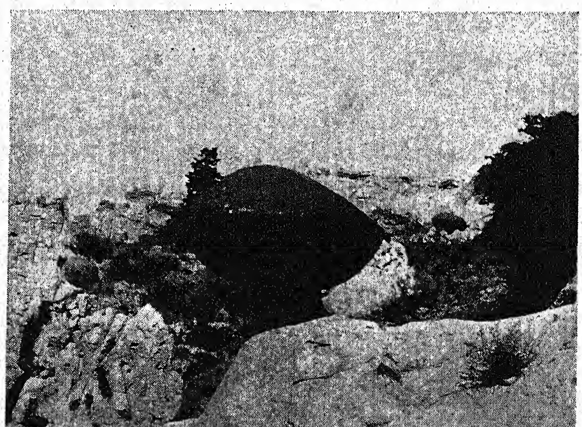


Fig. 130.—Concretions formed by cementation of sandstone with iron oxides, Fergus County, Montana. (*Photograph by W. A. Tarr.*)

Calcite is the most common mineral found in them. A very interesting feature of these veins is the arrangement of their crystals, which started

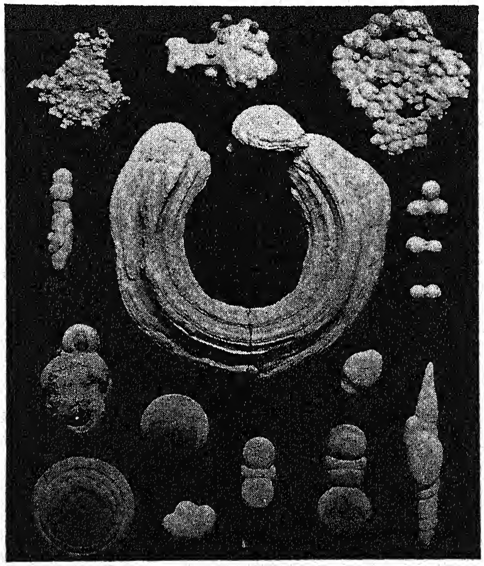


FIG. 131.—Calcareous concretions from Champlain formation along Connecticut River. (*Collected by W. A. Tarr.*)

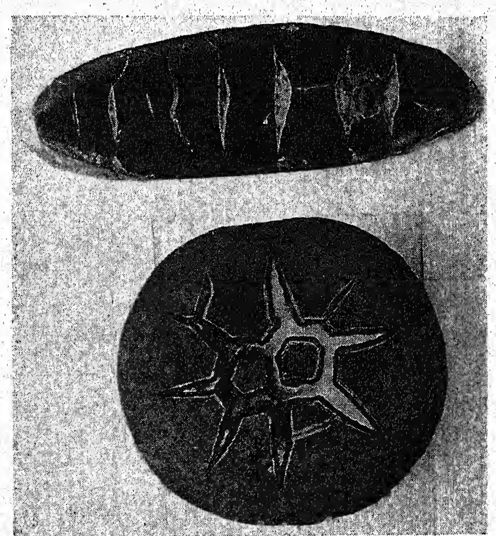


FIG. 132.—Septaria from northeastern Kansas. (Upper) vertical section; (lower) horizontal section. One-fourth natural size.

growing on the walls of the opening and grew outward at right angles to them (Fig. 127). If the crystals from the two sides have not filled the

opening, a cavity lined with crystals is left, forming what is called a *vug* (Fig. 127).

Special Deposits Formed in the Rocks.—Firmly cemented, rounded masses formed locally in porous rocks are called *concretions.* They are formed by the deposition of material at some point and the addition of more around it, the grains of the original rock being included in the con-

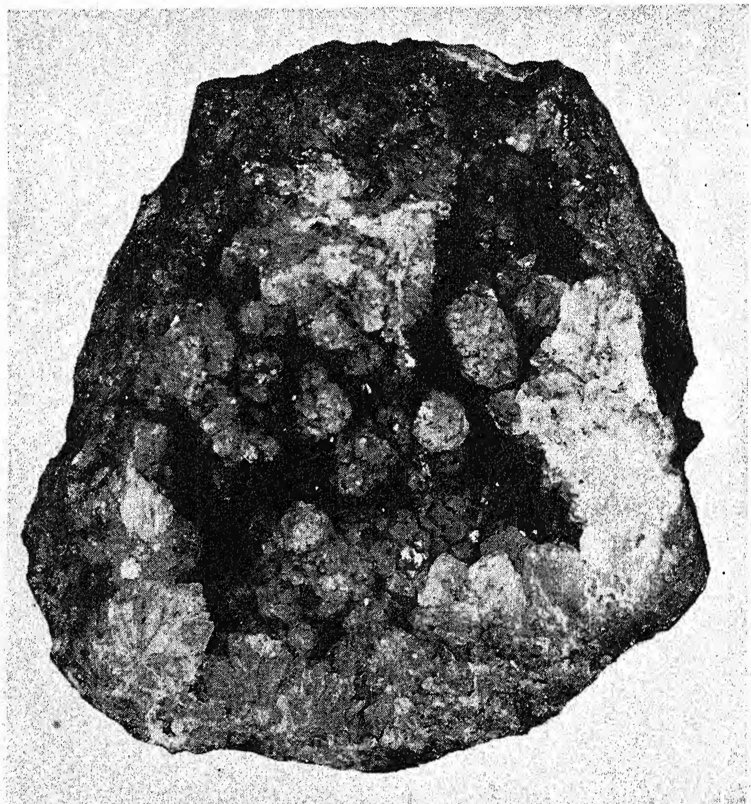


FIG. 133.—Geode lined with quartz. About natural size.

cretion (Fig. 128). Such concretions are, of course, of later origin than the rocks in which they occur. Large concretions, some 10 feet or more in diameter (Fig. 129), may be formed in this manner. In shape they may be spherical, elliptical, or very irregular (Figs. 130 and 131).

Septaria are concretions in which cracks developed by shrinkage were later filled with calcite or some other mineral (Fig. 132). These cracks developed in the interior because the material there dried after that of the exterior had become hard. The ground water that furnished material to fill the cracks entered through one or more of them that had extended to the exterior of the concretion.

The *caliche,* already mentioned, represents another special depositional feature. It occurs just below the surface in arid or semiarid regions where evaporation is rapid. As the water evaporates at or near the surface, more water moves up from below to take its place, and it too is evaporated and so deposits the mineral matter it contains. The deposit is usually calcium carbonate and it may be a few inches or many feet in thickness. Soil may or may not be present over the caliche.

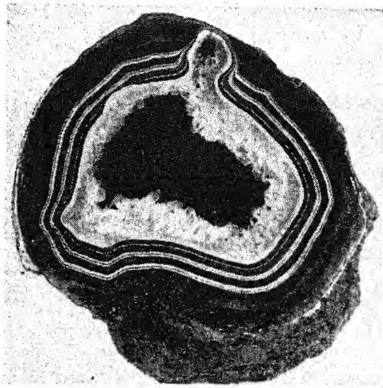


Fig. 134.—Agate showing channel through which the solutions entered. Brown agate inside of quartz crystals. About one-fourth natural size.

Geodes (Fig. 133) are formed by the deposition of material upon the inside of rounded or irregular cavities in the rocks. They are lined with crystals (usually of quartz, calcite, or dolomite) that point inward. In this they resemble a vug; in fact, the way in which geodes are formed is similar to the formation of a vein. If a cavity is being filled with quartz

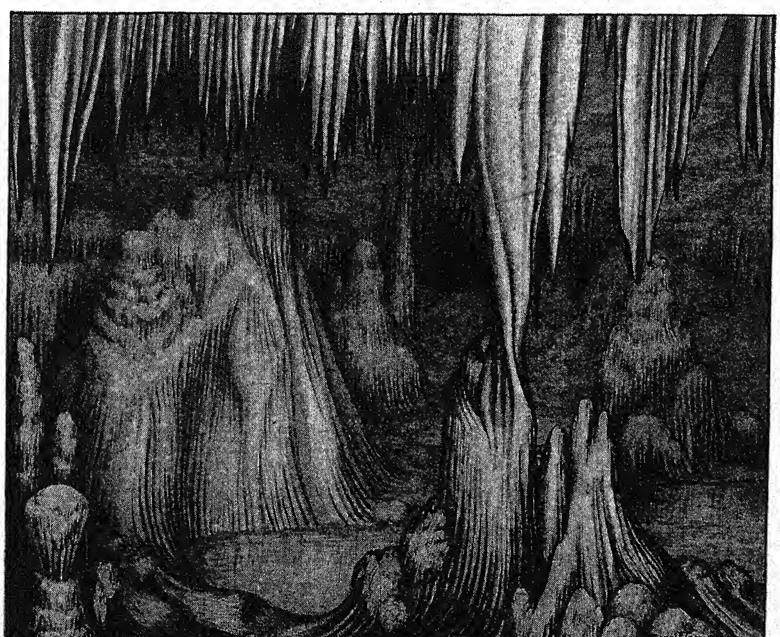


Fig. 135.—Stalactites and stalagmites in Luray Cavern, Virginia.

introduced as colloidal silica and the rate of deposition is fast, a fine-grained variety of quartz is deposited in alternating and colored bands.

This variety of quartz is known as *agate* (Fig. 134). The different colors in most agates are due to the presence of varying amounts of hematite (red) and limonite (brown or yellow).

Stalactites and *stalagmites* (Figs. 135 and 136) are deposited by ground waters in large openings (caverns) above the water level. The conditions that favor the formation of these features are that a water containing calcium carbonate in solution should drip or trickle from the

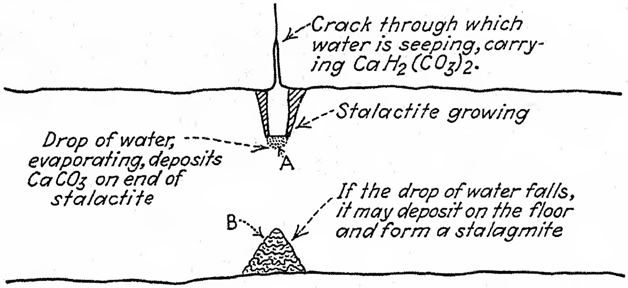


FIG. 136.—Sketch showing development of stalactites and stalagmites.

roof of a cavern slowly enough for the water to lose its carbon dioxide and thus cause the deposition of the calcium carbonate. If deposition occurs on the roof of the cavern, the deposit assumes a shape like an icicle and is called a "stalactite" (Fig. 136-A); if it occurs on the floor a rounded mass called a "stalagmite" (Fig. 136-B) is built up. The two forms may join and become, in the language of a negro guide in Mam-

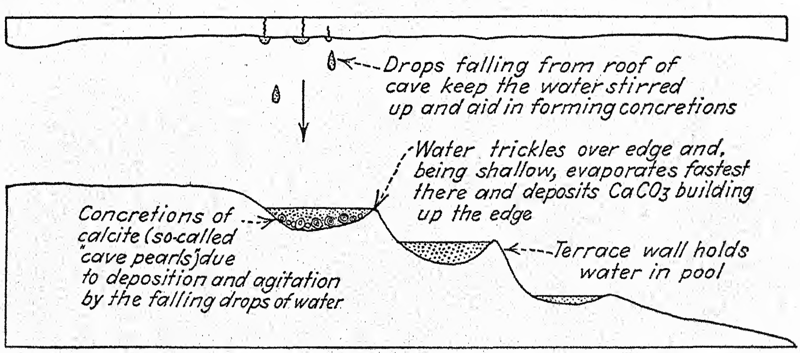


FIG. 137.—Sketch showing development of terraces on stalagmites and of concretions in the depressions.

moth Cave, "stick-tights." During the early stages of growth stalactites are hollow (Fig. 136-A) and grow dominantly at the lower end; later, after the opening is closed, the water flows down the outside and deposition occurs all over the surface. The canopy-like masses in caverns are the result of the union of adjacent stalactites through the deposition of material on the outside. The surface of many stalagmites is covered with great numbers of small terraced pools in the bottom of

FIG. 138.—Petrified Forest, Adamana, Arizona. (*Photograph by W. A. Tarr.*)

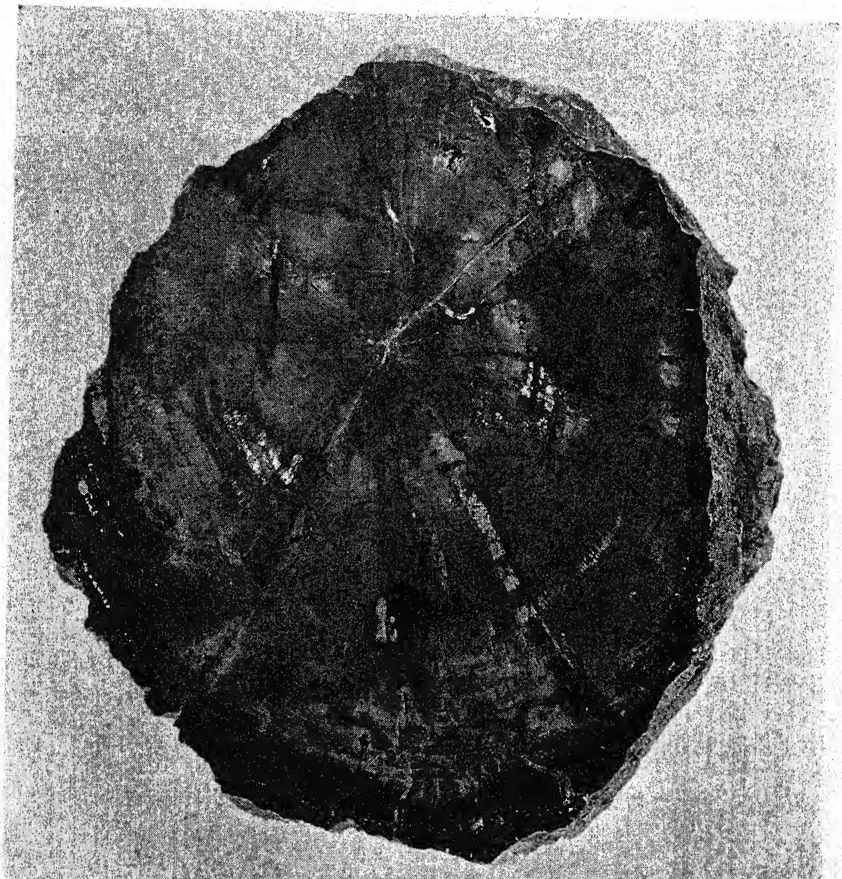


FIG. 139.—Polished section of petrified wood from Petrified Forest, Adamana, Arizona. Slightly reduced.

which are rounded calcite pebbles or concretions (so-called "cave pearls"). The terraces form by the deposition of calcium carbonate as carbon dioxide escapes from the shallow water trickling over the stalagmite (see Fig. 137). The concretions formed in the pools are the result of the deposition of calcium carbonate about nuclei. Their rounded form is further determined by the agitation of the pools by falling drops of water. Stalagmites produce a banded calcareous rock known as *onyx marble*, which is cut and polished for use in interior decoration.


FIG. 140.—Birch wood replaced by limonite. One-half natural size.

Replacement of minerals is an important function of ground water. The replacement of one mineral by another of entirely different composition is well illustrated when calcite (calcium carbonate) is dissolved out, one molecule at a time, and another mineral, such as quartz (silica), is substituted for it. By means of a partial replacement, one mineral may change into another of a composition not entirely different; for example, pyrite, which occurs commonly as cubes and consists of one part of iron (Fe) and two parts of sulfur (S), may be changed into limonite (an oxide of iron) by the removal of the sulfur and the addition of oxygen and water. The limonite retains perfectly the cubic form of the pyrite. A mineral which thus possesses the shape of another is called a *pseudomorph*. The name is apt, as the word "pseudomorph" means "false form."

Petrifaction is the replacement of organic material by some mineral, making it like a rock. The most common example of this change takes place when a piece of wood is buried in the ground and water bearing some colloidal silica or iron in solution soaks into it. The woody tissues are removed, molecule by molecule, and the mineral is deposited in their place (Fig. 138); thus the minutest details of the wood are preserved, even the exterior of it showing the cell details. Wood that has been replaced by quartz is very hard and takes a fine polish (Fig. 139). Petrifaction by iron oxides is less common, but Fig. 140 shows a piece of birch wood that was replaced by limonite while the original bark was preserved.

Surface Deposits Formed by Ground Water.—The common type of surface deposits made by ground water is that made by springs and geysers. Deposition by spring waters is due to lowering of temperature,

FIG. 141.—Deposition of calcium carbonate by Mammoth Hot Springs, Yellowstone National Park. (*Photograph by W. D. Keller.*)

loss of gases, and, to a less extent, evaporation. The deposited material, which usually accumulates around the opening of the spring, is called *calc-tufa* because of its porosity. The deposit at Mammoth Hot Springs,

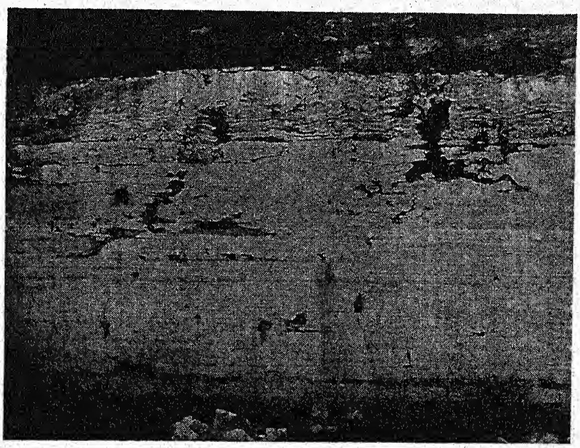


FIG. 142.—Quarry face in travertine deposits northeast of Rome, Italy. The narrow bands represent the layers deposited by the water. (*Photograph by W. A. Tarr.*)

Yellowstone National Park (Fig. 141), is a good example of this type. Some deposits spread far and wide over the surface, as do those occurring about 15 miles northeast of Rome, Italy (Fig. 142). These deposits cover an area of several square miles and have furnished *travertine* (the name applied to the more compact spring deposits of calcium carbonate) that is

hard enough to use for building purposes. This stone has been quarried and used for 2,000 years and at present is extensively used for interior decoration throughout the United States. A series of waterfalls caused by spring deposits of calcium carbonate occurs in a stream in Oklahoma.

The material deposited by geysers is largely silica; hence its name *siliceous sinter* (Fig. 143 *A*). This material is light colored and very porous. It is deposited chiefly as a result of the loss of gases and a

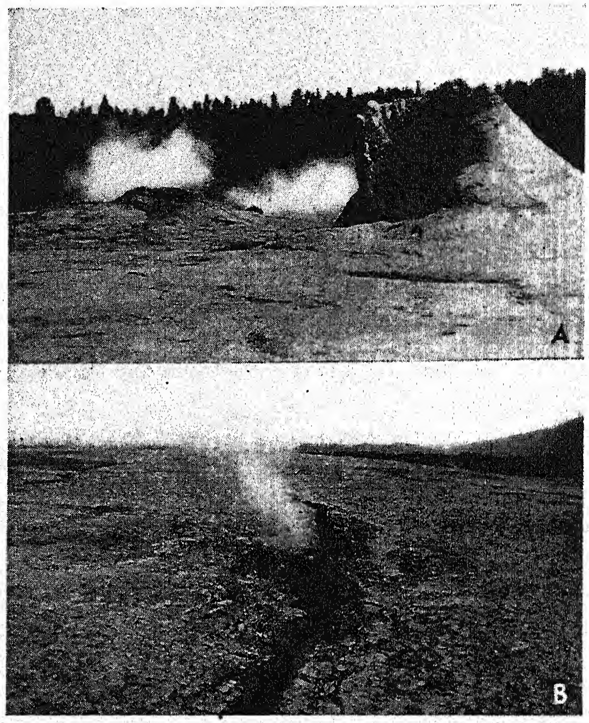


FIG. 143.—(*A*) Siliceous sinter deposited about geysers in Yellowstone National Park. (*Photograph by W. A. Tarr.*) (*B*) Siliceous sinter deposited by hot springs at Steamboat Springs, Nevada. (*Photograph by W. A. Tarr.*)

lowering of the temperature of the water. Small plants (algae) that live in some geysers make use of silica in their structure and thus assist in building up the siliceous deposits. A few hot springs of volcanic origin are also depositing silica. Such springs are those at Steamboat Springs, Nevada (Fig. 143 *B*).

Summary.—Owing to the various causes, ground waters deposit their mineral matter below the surface as cements, veins, concretions, geodes, agates, stalactites and stalagmites, pseudomorphs, petrified wood, and caliche; and upon the surface as calc-tufa, travertine, and siliceous sinter.

Results of the Solution Work of Ground Water.—Having considered the load of the ground water and its disposal, we shall now study the

results effected by the solution work upon the rocks themselves. Briefly, these results are:

1. Additional pore space in the rock.
2. Roughened surface of the rock.
3. Stylolites.
4. Cone-in-cone.
5. Widened joints and sink holes or sinks.
6. Caverns, lost rivers, natural bridges, karst topography, uvalas.

Additional Pore Space.—Since material is removed from the rocks by ground water, their pore space will be increased unless deposition or

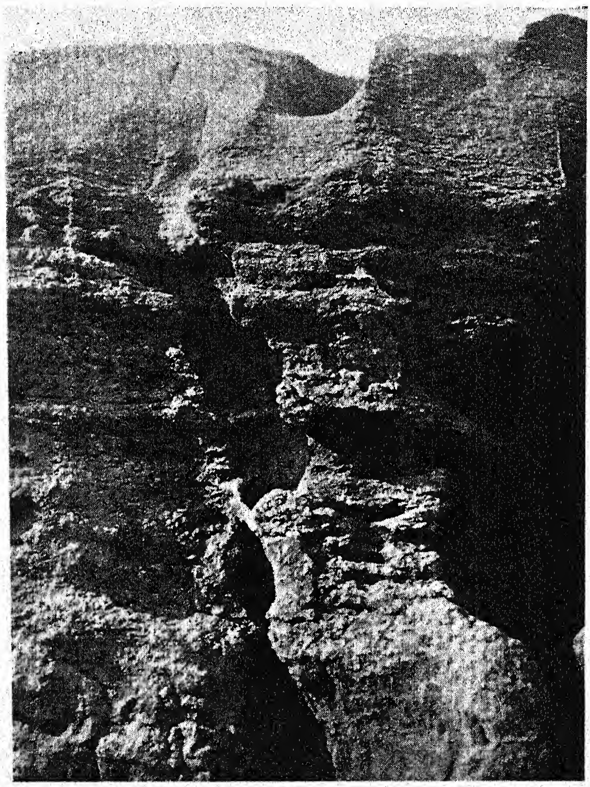


FIG. 144.—Roughened surface of limestone produced by solutions, Carthage, Missouri. (*Photograph by W. A. Tarr.*)

slumping occurs to fill it up. Some rocks become extremely porous, though as a rule the increase in the pore space weakens the rock so that slumping takes place.

Roughened Rock Surface.—The surface of the solid rock, whether it is exposed or in contact with the mantle rock, is the scene of the greatest amount of solvent work. If the soluble rock is, like the carbonate rock limestone, composed of one mineral, the irregularities produced on the

surface are due chiefly to differences in the size of the mineral grains (Fig. 144). In other rocks the roughened surface may be due, in addition, to differences in the mineral composition, as some minerals are easily

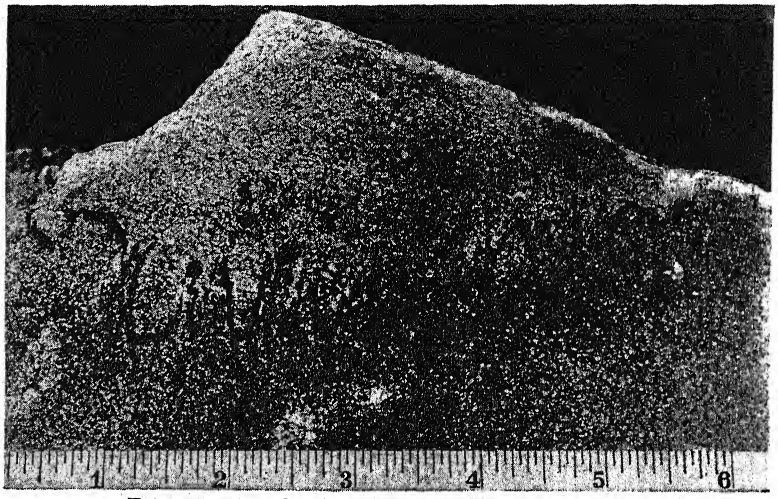


Fig. 145.—Stylolite in limestone, Carthage, Missouri.

attacked and removed leaving pits on the surface.

Stylolites.—Stylolites (Fig. 145) are vertically striated columns, pyramids, or cones occurring usually in nearly horizontal bands in limestones, dolomites, and, rarely, in other kinds of rocks. Stylolites are developed by the solvent work of water in connection with the pressure under which the rocks exist. The columns overlap each other and are capped by a dark insoluble clay. Lines of small stylolites, ½ inch or less in length, resemble suture joints and are so called by quarrymen. A stylolite

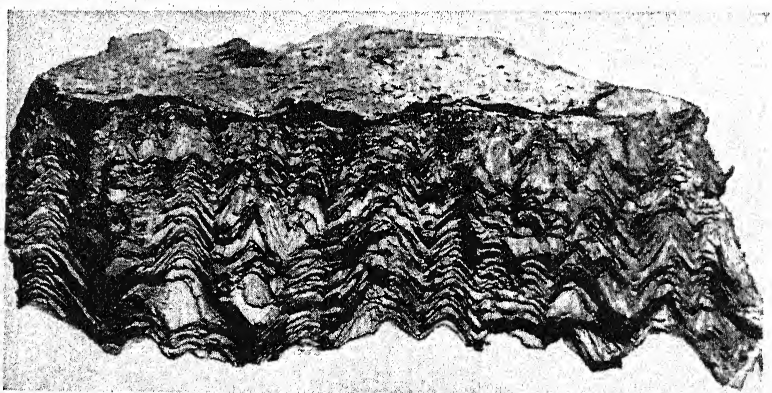


Fig. 146.—Cone-in-cone from Perry County, Kentucky.

increases in length by the solution of more of the rock at the end of the column, the column itself being protected from solution by the cap or coating of clay. Some stylolitic columns are 8 or 10 inches long. Stylolites are a bad feature in many limestones which otherwise would be well suited for building purposes.

Cone-in-cone.—Cone-in-cone is formed by ground water in a fibrous variety of calcite that occurs in sedimentary rocks. It consists of a series of cones resting one inside the other (Fig. 146), and occurs in patches a few feet across. The cones are usually 1 or 2 inches in height. The cone shape is believed to be initiated by a special fracture that develops in fibrous calcite, the solutions then moving along the cracks produced by the fracture.

FIG. 147.—Limestone showing solution channels, some of which contain clay, Carthage, Missouri. (*Photograph by W. A. Tarr.*)

Widened Joints and Sink Holes or Sinks.—It is inevitable that the walls of a joint or fissure along which water is moving will be attacked and some of the materials removed if there are soluble materials in the wall rock. The joint may thus become a wide opening through which the water moves freely (see Fig. 125, page 126). Insoluble materials may accumulate in the channel of this underground stream, or material from above may be carried down into it (see Fig. 147), and thus the circulation of the water and consequently further solution work would be confined largely to the contact along the walls. The opening would thus be more rapidly enlarged, and if the rate of solution exceeded the rate of accumulation of insoluble materials a depression would develop on the surface. Such depressions are known as *sink holes* (Figs. 123, page 123; 148, and 149) and are usually found above a cavern system into which the downward-moving water drains. In some sink holes surface water escapes under-

ground; in others the surface opening becomes closed and the water then accumulates in the depression to form a pond or small lake (Fig. 149).

Caverns, Lost Rivers, Natural Bridges, Karst Topography, and Uvalas.—*Caverns* are merely joints that have been exceptionally enlarged by the

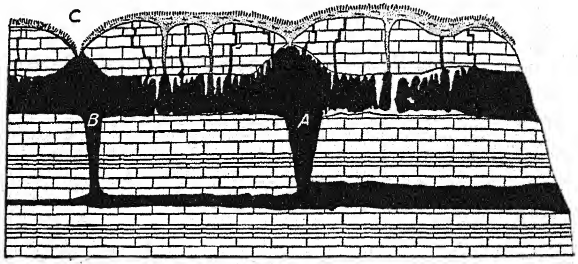


FIG. 148.—Diagram showing system of solution openings in limestone. Note stalactites and stalagmites. (*A* and *B*) Pits leading from upper to lower caverns. (*C*) Sink hole. (*After O. E. Meinzer, U. S. Geol. Survey Water Supply Paper* 489, *p.* 116, 1923.)

solution work of the ground water that flows through them. Inasmuch as the circulation must be fairly rapid to bring about much solution work, they are generally formed in the vadose-water zone. Some caverns are of great size, and are visited annually by thousands of people as scenic wonders. Famous caverns in the United States are the Shenandoah and

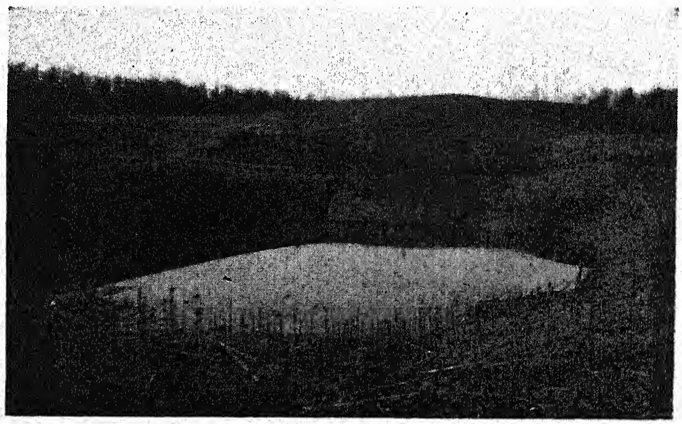


FIG. 149.—Sink-hole topography near Sparta, White County, Tennessee. (*Photograph by Willard F. Bailey.*)

Luray (Fig. 135) caverns in the Shenandoah Valley, Virginia; Mammoth Cave in central Kentucky; and Carlsbad Cavern in southeastern New Mexico. Large caverns are developed only in soluble rocks such as limestones, dolomites, gypsum, and salt. Caverns are most common in horizontal rocks (see Figs. 123, page 123, and 148), but they may also be developed in inclined rocks, as are the Shenandoah Caverns.

The water in a cavern collects into a stream (many are of considerable size) in the lower part of the cave. This stream finally joins the nearest

large river, reaching it either by an underground passage or after flowing out of the cavern. Many large springs are undoubtedly the outlets for underground streams (Figs. 123, 150, and 156, page 144). Surface streams that sink underground and reappear miles away are not uncommon in regions of limestone rocks. Such streams are known as *lost rivers* (Fig. 150). The course of these streams underground is either a cavern or a cavern in the process of formation.

A stream flowing through a cave lowers its bottom at the same rate at which the stream it enters is being lowered. Thus in the upper part of the chambers of many caverns, the evidence of the former courses of streams may be seen. Once a fairly large chamber is developed, the solution work of the stream is aided by blocks' falling from the roof. If a cave is near the surface, the roof may fall in, which is another method of forming a sink hole.

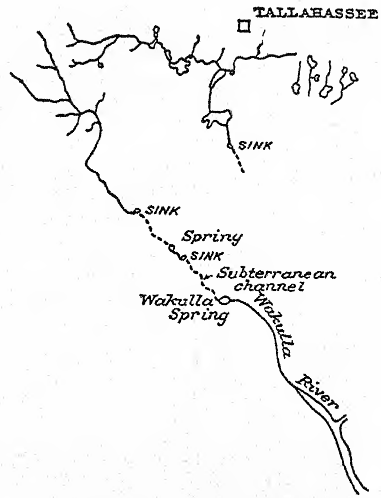


FIG. 150.—Drainage system of Wakulla River, Florida. Note relationship of the lost river (dashed line) to sinks and springs. (*After Meinzer U. S. Geol. Survey.*)

Some sink holes become elongated in the direction of the underground stream while a portion of the roof is left spanning the stream; these residual portions are known as *natural bridges*. The famous Natural Bridge of Virginia (Fig. 151) is more than 200 feet above the water. A highway passes over the top of it. Natural bridges are also formed as follows: the water of some waterfalls having found an outlet through joints behind and beneath the falls to emerge at a lower level follows that channel entirely when the opening has been worn large enough. A bridge is thus left spanning the new course of the stream. At Double or Trick Falls (Fig. 152) in Glacier National Park an early stage in such a development of a natural bridge may be seen.

A region containing many sink holes usually has a rough surface (Fig. 149) and the underlying rocks are commonly exposed on the sides of the sink holes. The name *karst topography* is applied to such an area. Later, after ground water has removed more material from below and the sink holes become connected, a broad basin floored with good soil is formed. This basin is called a *uvala*.

MECHANICAL WORK OF GROUND WATER

We have already emphasized the point that the dominant work of ground water is chemical, but we must note also the chief results of

mechanical work. The mechanical work is accomplished by the movement of the water and therefore becomes possible whenever the underground stream attains a size that enables it to move rapidly and transport solid particles of rock. This process is common in many caverns. The sands, gravels, and muds in the lower part of Mammoth Cave are evidence of the ability of ground water to carry material mechanically.

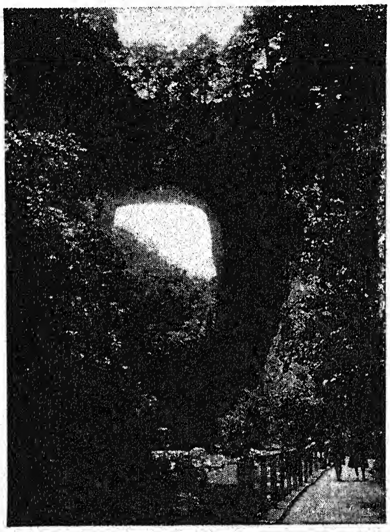


FIG. 151.—Natural Bridge, Virginia. It is a portion of a cavern roof left spanning a stream. (*Photograph by W. A. Tarr.*)

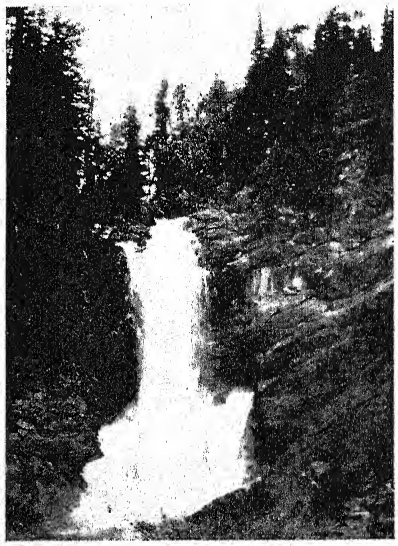


FIG. 152.—Double or Trick Falls, which shows a stage in the development of a natural bridge, Glacier National Park. (*Photograph by W. D. Keller.*)

Common results of the mechanical work of ground water that can be noted at the surface are *soil creep*, *landslides*, and *rock streams*. Downward movement of a rock mass whose weight has been increased by water saturation begins if its position is insecure. An important contributing factor in causing creep, landslides, or rock streams is the slipperiness of

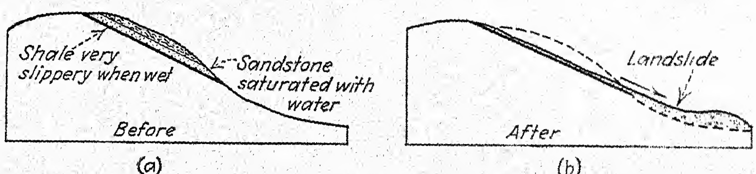


FIG. 153.—Sketch illustrating how a landslide may occur.

clays and shales when wet. Thus the surface of a clay or shale which lies beneath a saturated porous rock becomes an excellent surface along which the overlying material can move (Fig. 153). For these reasons boulders creep down a slope and great masses of rock break away on hill or mountain sides and plunge downward.

In numerous places in the Rocky Mountains, rock streams consisting of great masses of broken rock are moving slowly down the valleys.

FIG. 154.—Rock stream on Mt. Etna, Colorado. Length of stream, over a mile. (*After R. D. Crawford, Colo. Geol. Survey Bull.* 4, *p.* 34.)

FIG. 155.—Near view of the rock stream on Mt. Etna, Colorado. (*Photograph by W. A. Tarr.*)

Some of these streams are miles in length (Figs. 154 and 155). In the San Juan Mountains of Colorado tremendous volumes of rock are moving down the sides of the mountains and thence down the streams. The

Mountains That Walked in China illustrate a similar phenomenon, though on a tremendous scale, for there the area involved covered hundreds of square miles.[1]

THE FATE OF GROUND WATER

We have discussed the work of ground water beneath the surface and have referred to some of its deposits at the surface. In this closing part of the chapter we shall dwell especially on what finally becomes of the ground water.

A portion of the meteoric water that goes underground *enters into combination with mineral matter* and thus remains locked up in the minerals below the surface. Clay minerals for example, contain about 14 per cent of water; other hydrous minerals contain less, others more, but this percentage indicates that if many such minerals were formed considerable water would remain underground. Aside from this is the water that has passed into the minute rock openings (called *capillary openings* because they are hair-like in size) and stays there.

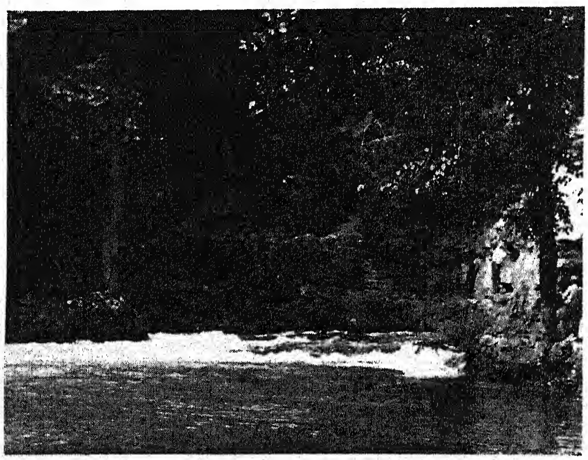


FIG. 156.—Big Spring, Carter County, Missouri. At its emergence it is two or three feet higher than the level of the stream into which it flows. (*Photograph by W. A. Tarr.*)

The larger part of the ground water, however, finds its way back to the surface and into the air by means of *evaporation*, either directly from the soil or from the leaf surfaces of plants. It is this water (that is constantly being added to the air) that falls again as rain; for, as we have seen, only one-third of the total annual rainfall on the land surface reaches the sea to be evaporated there.

A portion of the ground water reaches the surface through seeps, springs, and wells. Though the amount of ground water that reaches the surface by these means is not so great as that which reaches it by

[1] See *Nat. Geog. Mag.*, vol. 41, p. 445, 1922.

evaporation, these features form very noticeable and striking surface phenomena and so will be described.

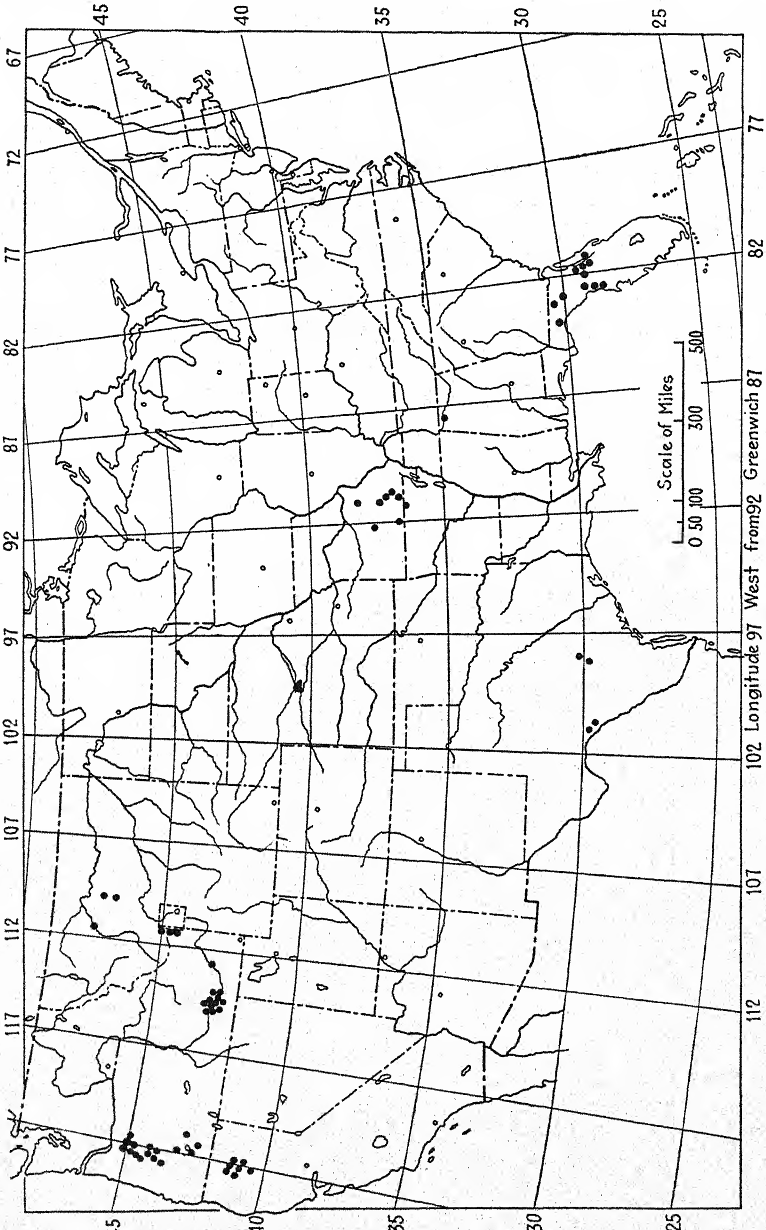


FIG. 157.—Map showing the distribution in the United States of the 65 springs having a minimum daily discharge of 64,600,000 gallons. Each of these springs would supply the daily needs of a city of 650,000 people. (*Meinzer, U. S. Geol. Survey Water Supply Paper* 557, p. 5.)

Seeps are important in the total amount of water contributed to the surface, though they do not seem important because of the slow movement of the water.

Underground streams of water issue at the surface as *springs* of varying size, temperature, composition, and permanency. Some springs are very large, being the outlets of underground rivers. The flow of Big Spring (Fig. 156), in Carter County, Missouri, averages over 276,000,000 gallons of water every 24 hours, which is double the amount of water used daily in St. Louis and Kansas City, Missouri. This spring is one of the largest in the United States, but there are many others (Fig. 157). Silver Spring in Florida, when flowing at its maximum, could supply the daily needs of Chicago and Philadelphia. Thousand Springs, Idaho, rivals Silver Spring in size. The large springs issuing from the lava beds along the north side of the Snake River between Milner and King Hill, Idaho, yield enough water to supply all the cities in the United States of more than 100,000 inhabitants, furnishing 120 gallons a day for each person.

The majority of springs are cold but a few are hot. Those of Hot Springs, Arkansas (temperature of water, 125 to 135°F.), Steamboat Springs, Nevada (185°F.), and Thermopolis, Wyoming (124 to 133°F.), are well known. The most noted examples of hot springs in this country, however, are those of Yellowstone National Park in Wyoming. These springs have a temperature nearly as high as the boiling point (200°F.) of water at the elevation of the park. Many of these springs, as the Mammoth Hot Springs (temperature 162°F.) at the north entrance, are of enormous size. Geysers are hot springs that erupt at intervals due to accumulations of steam below. As they are directly dependent upon hot igneous masses, they have been discussed fully under Volcanism.

Spring waters have had short or long journeys through the rocks and as a result have a wide range in their content of mineral matter, but all contain some, even though it is only a few parts per million. Some springs contain unusual kinds of mineral matter, and others, unusual quantities, so special names have been given them. Some spring waters contain mineral substances of curative value and thus are called *medicinal springs.* Many such springs, however, contain no more mineral matter than do the deep wells which supply many cities. Curative powers are also ascribed to some well waters, and again many of these claims are false. A bad odor such as that due to hydrogen sulfide (the same gas that is found in bad eggs) does not signify a water of curative value.

Most spring waters are potable but it should never be taken for granted that *all* springs are pure and thus suitable for drinking purposes, as they may have become contaminated by surface waters that have found their way downward into the main underground circulation or they may have come in contact with minerals that contain poisonous substances.

The permanency of springs is of passing interest only. If a spring flows all the year, it is a *permanent spring;* those flowing only after rainy periods are *intermittent springs.* Since springs are dependent upon the rainfall, even supposedly permanent springs may fail to flow after a succession of dry seasons.

Wells, like springs, vary in temperature, composition, permanency, and size. Since water is widespread in its occurrence within the rocks, most wells drilled furnish some water. However, wells that are several hundred feet deep may be dry, and that, too, in a vicinity of shallower productive wells. This is due largely to the character of the rocks, some being porous and others impervious, some jointed and others solid. It may also be due, however, to the other factors that control the amount of ground water. A fallacious idea prevails among some people that it is possible by the use of the branches of certain trees to find and follow from the surface the course of underground water. The turning of the branch in the hands of these persons is due entirely to the tension developed in the stick by holding it in a certain way and thus has, of course, no connection with water below.

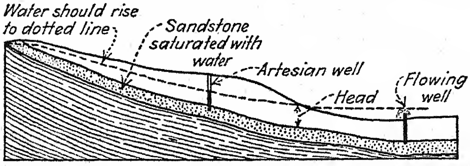


FIG. 158.—Diagram illustrating how artesian and flowing wells are formed.

If the water in a well rises above the level at which it was reached, the well is an *artesian well* (Fig. 158). This rise is due to the fact that the bed containing the water outcrops at a higher elevation than that at which it occurs in the well. Just so, the water from a tank is forced up to the second story of a house provided the house is below the tank. This pressure of the water is called the *head* (Fig. 158). If the pressure in a well is great enough, the water may flow out the top producing a *flowing well* (Figs. 158 and 159).

FIG. 159.—Flowing well, Boone County, Missouri. The water is rising from a depth of about 500 feet. (*Photograph by W. A. Tarr.*)

SUMMARY

Rain water, falling upon the surface of the earth, goes underground and there accomplishes chemical work by altering and dissolving the minerals of the rocks. The materials removed are either redeposited below or brought to the surface. Various features are formed by water below the surface and also by springs at the surface. The work of ground water is vital to man, as by means of it soil is developed and plant life supported.

CHAPTER VIII

THE OCEAN

In the two preceding chapters we have seen that by the work of the streams and ground water a vast quantity of material is removed from the surface of the land. The amount so removed in the United States every 8,000 to 10,000 years averages 1 foot of material from its entire land surface. The receiving station for such vast quantities of material is the ocean, though it is not necessarily their final resting place, for the ocean has encroached upon the land many times during the earth's history and the materials deposited in it during such periods were left upon the land when the water retreated into the deeper parts of the ocean bed. This material is then again attacked by the eroding agents and again moved oceanward.

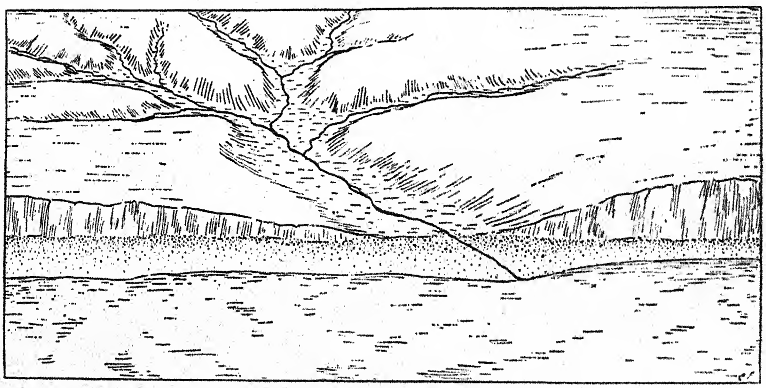


FIG. 160.—Sketch comparing vertical cutting (by streams) with horizontal cutting (by the ocean).

In addition to being the repository for eroded materials, however, the ocean is also an active eroding agent; hence its work is both depositional and erosional. The *erosive work* of the ocean is accomplished along its shores. The waves, which are the chief moving agents, are always at sea level, so that the ocean may be likened to a horizontal saw that is always cutting laterally at the same level, in contrast to the other eroding agents which cut vertically (Fig. 160). The cliffs along the sea are evidence of the lateral cutting of waves. The *depositional work* of the ocean occurs from the beach to deep water; but, inasmuch as the material deposited is derived from the land, the deposits near the shore greatly exceed in amount those of midocean. The ocean deposits are formed

both mechanically and chemically and so the sedimentary rocks which they give rise to represent the two methods of origin. Though we shall consider many phases of these deposits in connection with the work of the ocean, the methods of their deposition will be taken up in the next chapter on sedimentary rocks.

The Extent of the Ocean.—The ocean covers about three-fourths of the surface of the globe, or about 143,000,000 square miles. It extends beyond its true basin, overlapping about 10,000,000 square miles of the area of the continents (Fig. 161). This part of the ocean is called the *epicontinental sea* ("epi" means "upon"), and it is this portion with which we are most concerned as most of the work of the ocean takes place there. The width of the epicontinental sea ranges from almost zero to many miles, and its maximum depth is about 600 feet. The different parts of the ocean are all connected; hence the water level, or *sea level,* is the same in all and is the datum plane from which all land elevations are measured.

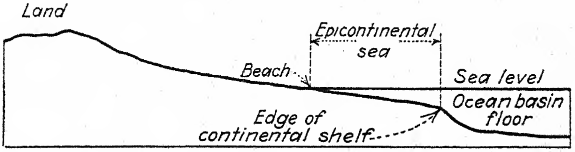


Fig. 161.—Sketch showing how the sea laps up on the continents.

The volume of water in the oceans is estimated at 323,722,150 cubic miles, yet this is only 1/4,500 of the volume of the earth. The average depth of the ocean is about 2.5 miles (13,000 feet). In this connection it is of interest to note that the average height of the land is about 0.5 mile (2,500 feet); hence the average height of the land above the average depth of the ocean is about 3 miles. If all the continents were cut down and the material deposited in the depths of the ocean, the water would be about 9,000 feet deep over the entire earth. The greatest depth known in the ocean is over 34,200 feet. This is in the Pacific just east of the Philippine Islands. About 4 per cent of the ocean floor lies below 18,000 to 30,000 feet of water.

Composition of Ocean Water.—We ordinarily think of the ocean as "salt water," but only about three-fourths of the mineral content of the ocean water is common salt. The average content of the mineral matter in sea water is about 3.5 per cent or 3.5 pounds to 100 pounds of water. The presence of the mineral matter in sea water increases the specific gravity of the water from 1 to 1.026. The total quantity present is about 4,800,000 cubic miles, enough to cover the United States and its possessions to a depth of slightly more than a mile.

The composition of the mineral matter in the ocean, as determined by Dittmar, is as follows:

Constituent	Percentage
Sodium chloride (salt) (NaCl)	77.8
Magnesium chloride ($MgCl_2$)	10.9
Magnesium sulfate ($MgSO_4$)	4.7
Calcium sulfate ($CaSO_4$)	3.6
Potassium sulfate (K_2SO_4)	2.5
Calcium carbonate ($CaCO_3$)	0.3
Minor constituents	0.2
Total	100.0

Traces of mineral substances other than those in the above list are contained in sea water. Some of these are iodine (2 parts in 1,000,000 parts of sea water); silica (2 parts in 1,000,000); and aluminum, iron, nickel, cobalt, copper, zinc, lead, gold, and silver.

Gases are also present in sea water. These are notably air (nitrogen and oxygen) and carbon dioxide. The air dissolved in sea water contains a higher percentage of oxygen than does the atmosphere. Cold water holds more gases than warm water, a fact that has probably had some effect upon the climates of the past. The sea water contains from 18 to 27 times as much free carbon dioxide as the air (the colder the water the larger the quantity of carbon dioxide). The carbon dioxide of the atmosphere absorbs heat, and because of this it has been suggested that if the ocean waters were cold enough to absorb large quantities of the carbon dioxide from the air the climate would become cold—even that a glacial epoch might result. The most important regulator of the temperature of the air, however, is its constituent water vapor, and any climatic changes would primarily be due to changes in the amount of this water vapor.

Source of the Mineral Matter in Ocean Water.—The larger part of the vast amount of mineral matter in the ocean is brought to it by the streams and ground water. Only a small portion is taken from the solid materials along the shores, as the chemical work of the ocean is

MATERIALS ADDED ANNUALLY TO THE SEA BY RIVERS

Constituent	Amount, metric tons
Calcium	557,670,000
Silica (SiO_2)	319,170,000
Sodium	258,357,000
Magnesium	93,264,000
Ferric and aluminum oxides	75,213,000
Potassium	57,982,000
Carbonate radical (CO_3)	961,350,000
Sulfate radical (SO_4)	332,030,000
Chloride radical (Cl)	155,350,000
Nitrate radical (NO_3)	24,614,000
Total	2,835,000,000

small. The preceding table, from the work of Clarke, is of interest as it gives some idea as to the large amounts of material added annually to the sea water by the rivers. This table gives the quantities by elements, oxides, and radicals, rather than by compounds, as most of the elements form more than one compound. It will be remembered, for instance, that sodium, calcium, and magnesium may all go off as carbonates, sulfates, or even chlorides. We therefore pay no attention to the amount of the compounds that are formed. The information in this table is of much interest, as these materials are the source of a part of the sedimentary rocks.

It is of interest to contrast the percentage composition of the average river water with that of the average sea water, for from the comparison we learn what elements remain in the sea water and what ones are deposited. The following table, from data compiled by Clarke, shows this comparison.

AVERAGE COMPOSITION OF RIVER AND SEA WATER

Constituent	Percentage amount	
	River water	Sea water
Calcium	20.39	1.197
Silica (SiO_2)	11.67	0.000
Sodium	5.79	30.593
Magnesium	3.41	3.725
Ferric and aluminum oxides	2.75	0.000
Potassium	2.12	1.106
Carbonate radical (CO_3)	35.15	0.207
Sulfate radical (SO_4)	12.14	7.697
Chloride radical (Cl)	5.68	55.480[1]
Nitrate radical NO_3	0.90	0.000
Total	100.00	100.000

[1] Includes 0.188 per cent of bromine.

A glance at this table shows that all the silica, iron, and aluminum and most of the calcium have been deposited; that, although most of the mineral matter going to the ocean is the carbonate, it also has been deposited; and that the chlorine and sodium have accumulated in the sea water in tremendous amounts.

Life in the Ocean.—Although living creatures are found throughout the ocean, the major part of all ocean life exists in the shallow epicontinental seas surrounding the continents. As this is also the zone of the major work of the ocean, the life in these waters plays a part in the deposits made there. A considerable part of the deposition of the

calcium carbonate, for example, is accomplished by organisms that use it for their shells.

MECHANICAL WORK OF THE OCEAN

The ocean accomplishes most of its work mechanically and only a very minor part chemically. The mechanical work of the ocean is of two different kinds: *erosive work* and *depositional work*. This depositional work is not only that connected with the large quantities of clastic material that are brought to the ocean by the rivers of the world, but a part (a minor part, of course) is concerned with the formation of deposits from the materials eroded by the waves from the rocks at the seashore. The erosional work of the ocean is concerned also with the process of reducing in size the fragments of rock that are brought in by the rivers.

THE MECHANICAL AGENTS

Just as the ability of a stream to accomplish mechanical work is dependent upon its velocity, so the mechanical work of the ocean (a comparatively quiet body of water) depends upon the very small part of its body that is moving. The moving parts of the sea are the *waves*, *currents*, and *tides;* hence these are the agents of the mechanical work of the ocean.

Waves.—Most of the mechanical work of the ocean is accomplished by the waves, which owe their origin to the wind that sweeps over the water. The stronger the wind and the longer it blows the larger are the waves. Waves consist dominantly of an up-and-down movement of the water but include also a forward movement at the immediate surface. The maximum movement of the water in a wave is therefore at the surface. The movement dies out rapidly downward, usually within a few feet, though rarely waves reach depths of 25, 50, or more feet. The chief force of the wave is developed when it breaks on the shore, whether on a beach of loose materials or upon a rock surface. Waves also break in the open ocean (then called "white caps") but accomplish no work there. Upon a beach having a wide, gently sloping surface the waves drag upon the bottom in the shallow water. This retards their movement, deflecting it upward and therefore increasing the height of the waves (*a*, Fig. 162). At the same time, the top or crest of the wave, since it is able to move faster, rushes forward (shown in *b*, Fig. 162) until it overhangs the slower-moving trough and, lacking support, breaks (*c*, Fig. 162, and Fig. 163).

As a wave breaks on the beach, which is the place of active wave work, the water is violently agitated and the pebbles on the bottom are rubbed and ground against one another. These pebbles tend to become flatter than those made by running water because the movement of the waves is a back-and-forth sliding movement. Some beaches become

covered with flattened or elliptical pebbles, two to six inches in diameter, and are then known as *shingle beaches.* The pebbles and boulders of the beach are efficient tools with which the waves accomplish much work. Waves that are driving in upon a rocky shore where the water is deep enough to prevent much retardation at the bottom will break upon the

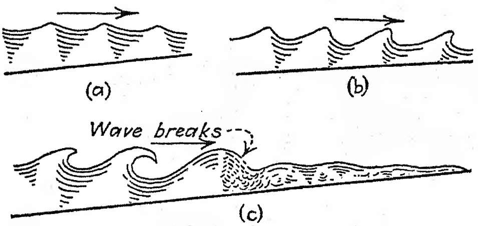


FIG. 162.—Sketch of a wave breaking on a beach.

rocks. During storms the force of the blows may amount to hundreds of pounds per square foot. If these blows are rapidly repeated, immense damage may be done to piers and sea walls during a single storm. Enormous blocks of rock, weighing tons, have been shifted about by storm waves. As a matter of fact the exceptional waves of storms, though occurring many years apart, may loosen and pry off more material than

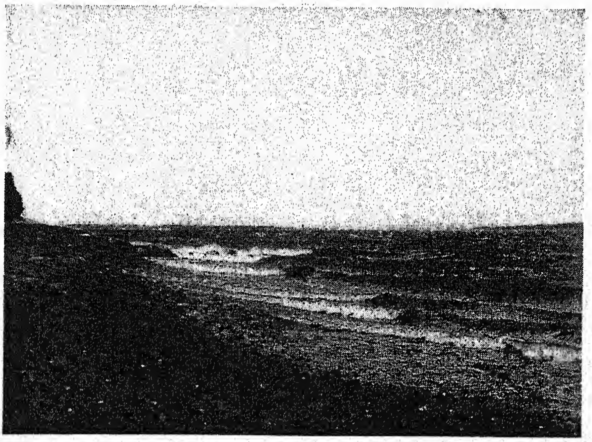


FIG. 163.—Several waves breaking diagonally on the beach at Seacroft, below Belfast, Maine. The three phases of wave motion (*a*, *b*, and *c* of Fig. 162) can be seen along each wave. (*Photograph by W. A. Tarr.*)

the ordinary waves can break up in the long intervals between the storms. It will be seen from this discussion that a broad shelving shore would be less effectively attacked by the waves than a steep rocky shore.

In deep water, the waves cannot use rocks as tools but must depend upon the weight of the moving water. They are aided, however, by the air in the joints of the rocks. The water rushing into the joints com-

presses the air, which in turn exerts a pressure upon the rocks. This process, repeated every few seconds, greatly assists the waves; in fact, in small caves along the shore, this compression and expansion cause whole blocks to be pried off from the roof and sides of the opening.

Another point that should be noted is that the belt of active work by the waves is limited in depth to the distance between high and low tide plus the height of the highest storm waves.

Currents.—Not only does the breaking of the waves accomplish work, but waves cause currents which effectively aid in the work. The drift of the water at the surface as the wind blows over it sets up a current which moves in the direction of the wind. These currents occur dominantly along the shore, where the tide, also, aids in their formation. The shore currents move in any direction along the shore (Fig. 164). When the waves are breaking rapidly, shore currents are strong; at other times

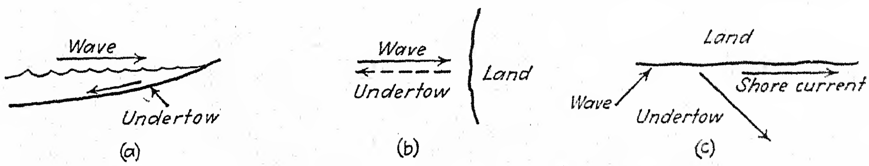


FIG. 164.—Sketch showing development of shore currents.

they move slowly. The strongest shore currents are those formed on the floor of the beach by the backward flow of the water after a wave has broken. These are known as the *undertow* (Fig. 164), which is very important in aiding the work of the waves. Currents are also produced in the open sea, but there they are unimportant in the work of the ocean as they are largely slow drifts of water. Any shore current moving offshore also becomes unimportant save for transporting and distributing materials in suspension and solution.

Tides.—The tide creates strong currents along a rough indented shore, and these tidal currents aid in the work of the ocean. Also, the rise and fall of the tide, twice each day, widen the effective zone in which the waves can work. In some bays the tide has a rise and fall of 15, 20, or 50 feet.

SUCCESSIVE STEPS IN THE WORK OF THE MECHANICAL AGENTS

The work of the waves, currents, and tides (like that of streams and ground water) is accomplished in three successive steps: (1) *getting a load,* (2) *transportation,* and (3) *deposition.*

Getting a Load.—Though much clastic material of small sizes is contributed to the sea water by the streams and very minor amounts by glaciers and the wind, considerable quantities of material are obtained directly by the ocean itself through the *work of the waves* on the rocks of the shore. These loosened materials, *i.e., sand, gravel, pebbles,* and

boulders, are then used as tools with which to grind or hammer off more material from the rocks; in the process of which the tools themselves are ground to smaller sizes, and thus the ocean obtains through its own efforts much additional clastic material of the smallest sizes, *i.e.*, silt and clay.

Transportation.—Transportation of materials is accomplished by the *waves, the undertow and other shore currents, and the tidal currents.* These forces are not equally developed along any given shore, but all function in some degree. The methods of transportation are similar to those of the streams, *i.e.*, the material is moved by *sliding, rolling, saltation,* and *in suspension.* The major part is moved on the bottom; for, because of the much slower movements of ocean water, any material in suspension settles out rapidly. Owing to this fact the water along a shore is fairly clear unless violently agitated during storms.

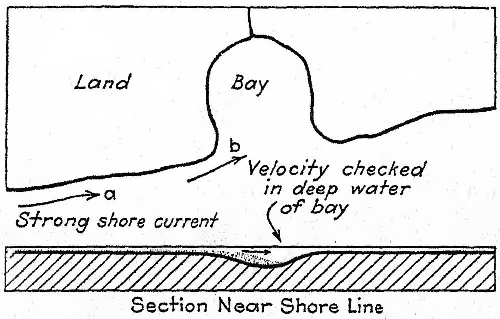


FIG. 165.—Sketch showing deposition due to check in velocity of a current entering the deeper water of a bay.

The material is transported toward the open sea by the undertow and other currents or it may be shifted along the beach by the lateral shore currents. If the direction of these currents is constant the transported materials are all moved one way along the beach, but if the currents vary in direction the materials are shifted back and forth.

Deposition.—Just as velocity is essential in enabling the waves and currents to pick up and carry materials, so a decrease in velocity will mean the deposition of their load. This loss of velocity is due dominantly to the shifting of the currents and waves into deeper or shallower water, and to a less extent, therefore, to the overloading of the ocean water by streams. A shore current, which in moving along a beach (*a*, Fig. 165) reaches a point (*b*, Fig. 165) where the shore turns inland to produce a bay, will continue straight ahead (following a law of all moving bodies). As it leaves the shore, however, it will enter deeper and deeper water. This deep water is not moving; hence the velocity of the current will be checked. As the materials which the current was shifting along the bottom will continue to follow the bottom, they will thus move downward

out of the zone of strongly moving water and so will come to rest in the deeper water of the bay. Smaller indentations along a coast will cause a correspondingly smaller checking of velocity and thus deposition on a minor scale. If a current shifts from deep into shallow water, the consequent increased friction with the bottom will retard velocity and deposition will result. The undertow in moving seaward from the beach encounters deeper water and, as it loses its velocity, deposits its load. In this way it builds up the sea floor offshore and so can move material farther and farther seaward. The very finest materials borne in suspension are carried many miles offshore (records show that materials from the Amazon River have been thus carried several hundred miles out to sea), but nevertheless they finally sink downward beyond the moving water of the current, through the still water below, and at last to the sea bottom.

For the most part the material worn from the land is deposited along the beaches but some is shifted offshore. There are many variations from the normal movement seaward. The waves that drive in on the shore move material up on the beach; the undertow drags it back. The battle is ceaseless, but the movement toward deeper water gains. Materials that are derived from the land, shifted seaward, and deposited are known as *terrigenous* (land-derived) *materials*.

EROSIVE FEATURES FORMED ALONG THE SHORE

Many interesting features along the shore testify to the erosive power of the ocean. Essentially all of them are due to the mechanical work

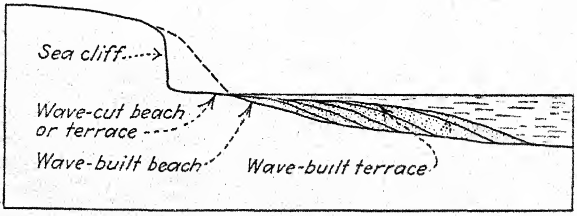


FIG. 166.—Sketch showing some features developed by waves and currents along shores.

of the waves and currents. Some of the features are *wave-cut beaches or terraces, sea cliffs, sea caves, chimneys, and natural bridges.*

A *wave-cut beach or terrace* is produced by the waves' cutting into a land surface of moderate relief (Figs. 166, 167, and 168). The beach varies much in width, depending upon the depth of the water, the force of the waves, the height of the land, and the character of the rocks. If the land is high, a *sea cliff* (Figs. 166, 167, and 168) will be developed as a result of undercutting by the waves. The height and steepness of the cliff will depend upon the height of the land above the sea and the rate of cutting by the waves. If the waves are strong and the rocks

weak (as are soft shales and sandstones or the chalk cliffs of England and France), erosion will be fast and the cliff may retreat a few feet a

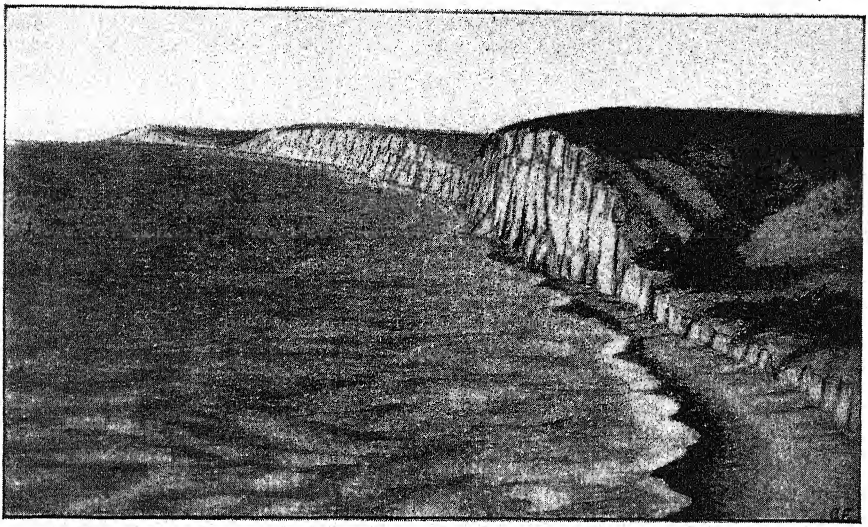


Fig. 167.—Waves (at high tide) developing a sea cliff and a wave-cut beach or terrace. (*Modified after D. W. Johnson, "Shore Processes and Shoreline Development," with permission of John Wiley & Sons, Inc.*)

year. Cliffs that are cut in hard resistant rock show no change in thousands of years.

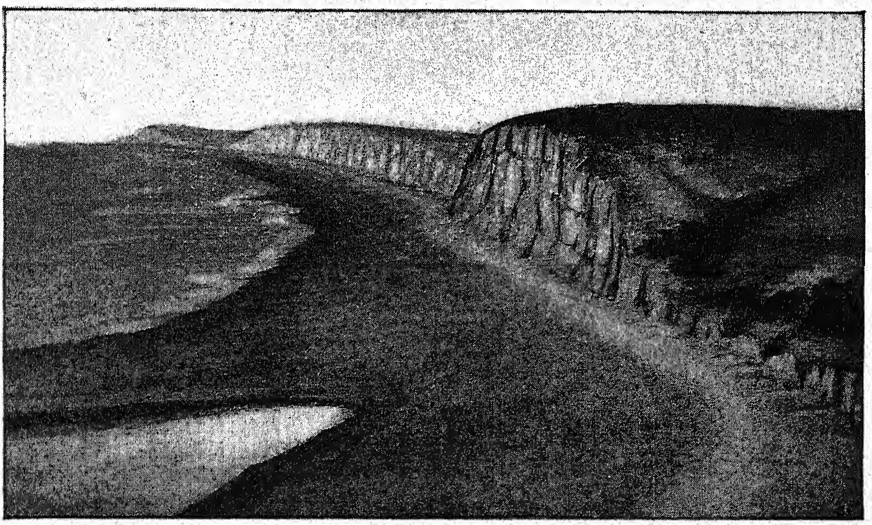


Fig. 168.—Same shore as that shown in Fig. 167, but showing the wave-built beach exposed at low tide. (*Modified after D. W. Johnson, "Shore Processes and Shoreline Development," with permission of John Wiley & Sons, Inc.*)

During the attack of the waves on the land many incidental features are formed, some of which are more or less striking in appearance. A

sea cave is a fairly common feature that is formed at the level of the waves by their cutting back along weak places in the rocks. Sea caves usually

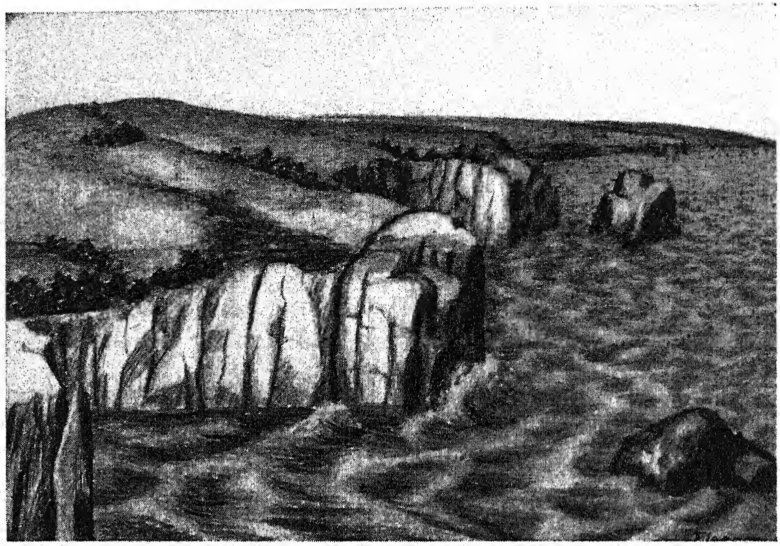


Fig. 169.—Sketch showing how vertical joints favor the development of stacks along a shore.

Fig. 170.—Stacks and sea cliffs, island of Capri, Italy.

develop in jointed rocks, especially if the joints are fairly horizontal and vertical. Solubility of the rocks is of some aid but sea caves are no more abundant in limestones than in other rocks. The Blue Grotto

near Naples, Italy, is a sea cave of interest because of the blue color on the interior. This color is due to light reflected from outside. The roofs of sea caves are eroded by the waves, aided, if the entrance is closed at high tide, by the compression of the air in the cave. The roofs finally break through to the surface (just as do those of the underground caves that form sink holes). During storms water may be ejected through this roof opening, giving rise to *spouting caves.*

FIG. 171.—Wave erosion at the base of a stack, Alaska. (*Photograph by W. W. Atwood, U. S. Geol. Survey.*)

If the rocks along a shore contain vertical joints, erosion along these joints is usually faster, whereupon the face of the cliff will become indented by these deeper cuts. As the erosion continues, vertical masses of rock will become separated from the cliff. These masses are called *chimneys* or *stacks* (Figs. 169, 170, and 171). During the process of separation, when the waves have cut through below but there is still a rock connection above, a *natural bridge* exists (Figs. 172 and 173).

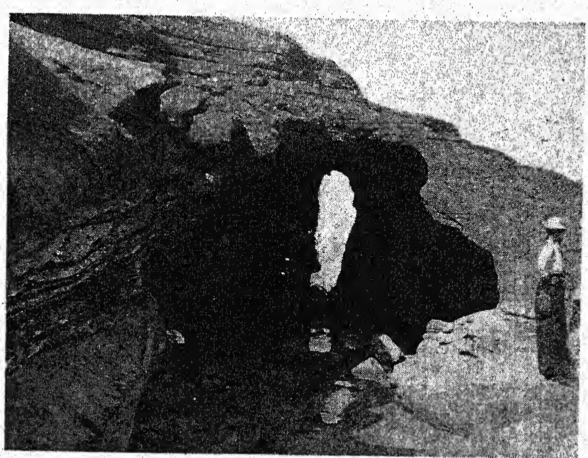


FIG. 172.—Natural bridge developed along a joint by wave erosion, La Jolla, California. (*Photograph by W. A. Tarr.*)

DEPOSITIONAL FEATURES FORMED ALONG THE SHORE

The deposits made along the shore by the ocean have numerous forms, the more common of which are *wave-built beaches, wave-built terraces, barrier beaches, spits, hooks, bars,* and *tombolos.* All of these deposits are the result of the mechanical work of the ocean.

The *wave-built beach* represents the major accumulation of material along a shore. The other features are, as we shall see, largely special extensions of the beach. The *wave-built terrace* (Figs. 166 and 168) results from the deposition in deeper water of material removed from the beach. If a beach is wide and nearly flat, large waves coming in commonly break a considerable distance offshore. At this point a ridge of sand is usually developed, as the waves and the undertow shift material to this point from both sides. This ridge may be built above the water level by the help of storm waves and then becomes a *barrier beach* (Fig. 174). The lagoon back of a barrier beach is gradually filled up, becomes a swamp, and finally the swamp also disappears; and thus the area has been reclaimed from the sea.

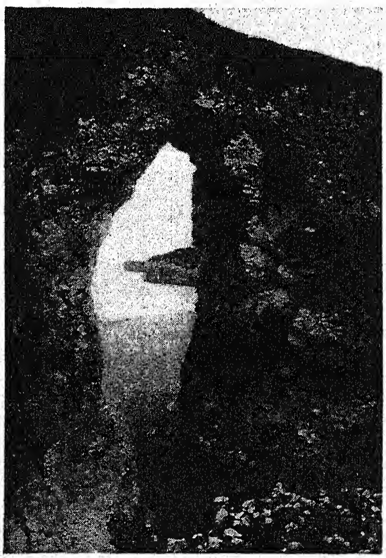


FIG. 173.—Natural bridge cut by waves in chalk on north coast of Ireland near Port Rush. Note another natural bridge in headland seen through arch. (*Photograph by W. A. Tarr.*)

As the shore currents move material along the beach, some form of deposition occurs wherever there is a change in the direction of the shore. If the shore line curves out toward the open sea, the shore currents fill in the inside of the curve and widen the beach, as at *a*, Fig. 175. The deposition that occurs as a shore current enters the side of a bay extends the beach out into the bay and a *spit* (Figs. 175 *c*, and 183, page 166) is formed. If the spit is built across the bay it becomes a *bar* (Fig. 175 *b* and Figs. 176 and 177) and the bay becomes a lake or lagoon (Fig. 175 *B*). If the bar extends from the mainland to an island it is called a *tombolo* (Fig. 178). It commonly happens that waves drive into a bay where a spit is being built and deflect the shore current inward so that the spit becomes curved, forming a *hook*. A strong river current entering a bay during the formation of a spit may change it into an outward-curved hook (Fig. 175 *d*).

All these depositional features are common along the sea shore, especially if the coast has numerous indentations and the water is not too deep. They are very abundant along the Massachusetts coast line, where the waves have an abundance of soft, loose material to work upon. On the other hand the Maine coast line is remarkably free from them, because the continental glaciers deepened the water along the shore and removed most of the soft rocks, and the waves have been unable as yet to alter the hard rock that is exposed. Along the

Atlantic Coast from New Jersey southward depositional features are abundant.

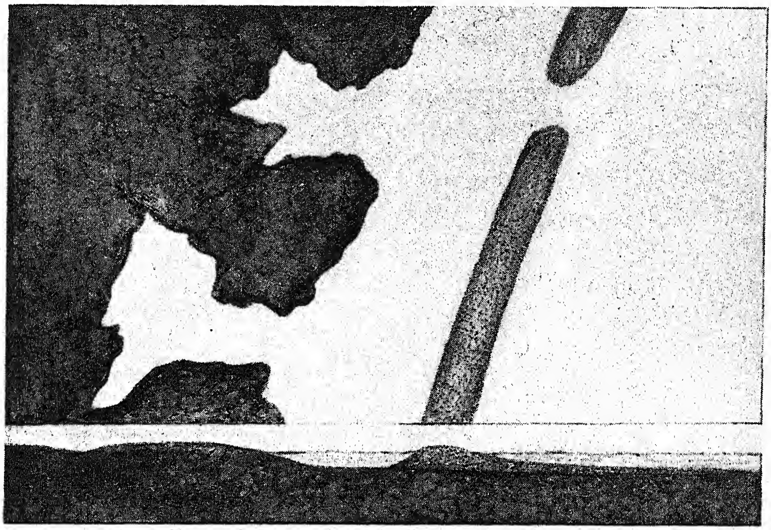


Fig. 174.—Sketch showing position and structure of a barrier beach.

THE CHANGING SHAPE OF THE COAST LINE

In studying the features due to erosion and deposition along the shore we have seen how the ocean itself is constantly modifying and

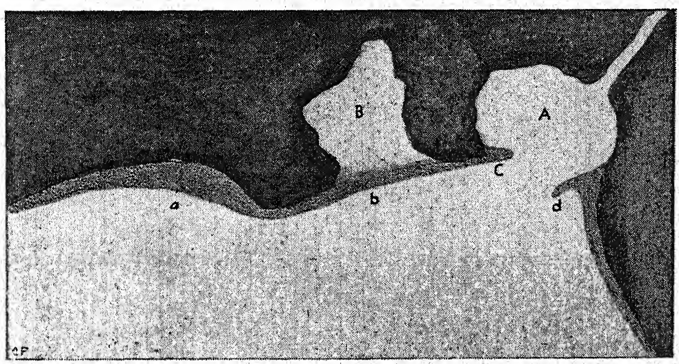


Fig. 175.—Sketch showing development of (*a*) beach; (*b*) bar; (*c*) spit; and (*d*) hook.

changing the shape of its coast line. A glance at the map of any continent will show how the shape of the coast line differs from place to place (Fig. 179). The actual outline of the coast is thus due to the *work* (*both erosional and depositional*) *of the waves and currents*, but this work may be interrupted and modified by three factors, *viz.*, *sinking of the coast*, *raising of the coast*, and *work of glaciers and streams*.

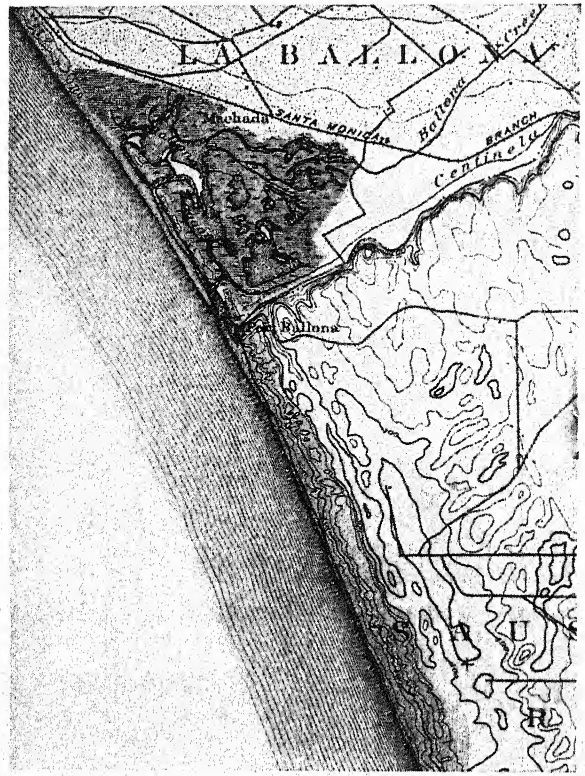


Fig. 176.—Map showing bar and lagoon on California shore. (Part of the Redondo, California, Quadrangle. Contour interval is 25 feet; 1 mile = 1 inch.)

Fig. 177.—Bar built across a bay. Lagoon at back being filled up.

The Production of an Adjusted Shore Line.—The effectiveness of the work of the waves and currents along a shore depends on various factors, among which are the existing *irregularities of the coast line, the character of the rocks,* and *the depth of the water* along the shore.

Projecting portions of land, such as capes, points, and other headlands (Fig. 169 and 170), are more vigorously attacked by the waves than are the rocks of the shore in reentrants, such as bays, sounds, and sea caves. The dominant modifications caused by the waves and currents, therefore, are the cutting away of the headlands and the deposition of the material

FIG. 178.—Air view of land-tied island produced by formation of a tombolo, Alaska. (*Courtesy of U. S. Navy Air Service.*)

in the quiet water of the nearest reentrant. This would mean a smoothing out of the shore line. If no other factors intervened and the waves and currents were thus allowed to complete their work, the final result would be an *adjusted shore line, i.e.,* one upon which the erosive work of the waves and currents was balanced by their depositional work.

An adjusted shore line, however, would not be perfectly straight unless the rocks of the shore were all of the same hardness. Thus, where the material is all sand, the shore line is straight or has long sweeping curves, as portions of the coast line of the Carolinas or of Texas. A coast line that is quite straight in general outline, however, has minor indentations, known as *cusps* because of their resemblance to a crescent moon. Cusps are the result of the adjustment of the direction of the waves to the direction of the shore line.

The depth of the water is also a factor in the effect produced on a shore line. Waves have less eroding power in shallow water and hence in such places cannot cut the land so rapidly.

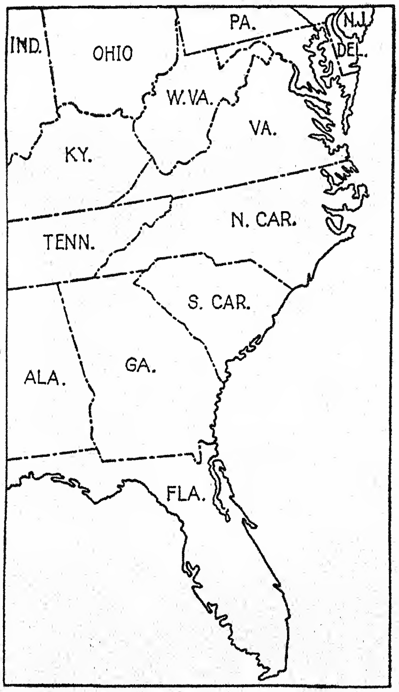


FIG. 179.—Map of southeastern United States showing smooth and irregular shore lines.

During the early stages in the development of an adjusted shore line by the waves and currents the irregularities are increased. This occurs very commonly by the production of spits and hooks (as can be seen at *c* and *d* in Fig. 175). Likewise, barrier beaches, whether connected with the mainland or not, increase the irregularities of a coast line. Also, during and by the formation of stacks (see Figs. 169 and 170), the coast line is rendered more irregular and longer; and when, by the deposition of the materials cut away, the stacks or islands are later tied to the mainland by tombolos (Fig. 178), the irregularity as well as the lengthening is further increased. Later, however, the spits and hooks are built entirely across the bays, forming bars; the lagoons back of the bars and barrier beaches become filled up; and, by more sedimentation's occurring along the tombolos, the land-tied islands become fully incorporated with the mainland. All this may result finally in producing a coast line of long sweeping curves (Fig. 176). The shore line of North Carolina (Fig. 184) is much

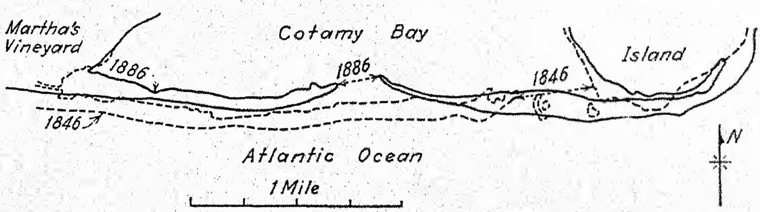


FIG. 180.—Map showing shore line of Martha's Vineyard, Massachusetts, in 1846 and in 1886. (*After Shaler, U. S. Geol. Survey*, 1885–1886.)

longer now than it will be when the lagoons back of the barrier beaches along the shore are filled up. Thus we see that the increase produced in the irregularities of a coast line is temporary, and as the period of filling in the indentations continues a coast line of long

sweeping curves will be produced. A good illustration of a shore line in the process of change is seen in Fig. 180, which represents a part of the south coast of Martha's Vineyard in 1846 and in 1886. Such

FIG. 181.—A dissected area along a sea shore.

FIG. 182.—Area of Fig. 181 after submergence. Shows drowned valleys and greatly lengthened coast line.

marked changes may occur in a few years where the waves and shore currents are especially active.

Effect of a Sinking Coast.—A factor that may interfere with the work of the ocean in adjusting its shore line is the sinking of the coast.

The effect that will be produced may be seen by a study of Fig. 181, which shows a dissected area having an irregular shore line; the same

FIG. 183.—Submerged area of Fig. 182 after work of producing an adjusted shore line has been renewed. Note sea cliffs, widened beaches, bars, tombolos, land-tied islands, and spits.

region after the land had sunk (Fig. 182), showing how the sea had entered the valleys of the rivers to variable distances depending upon

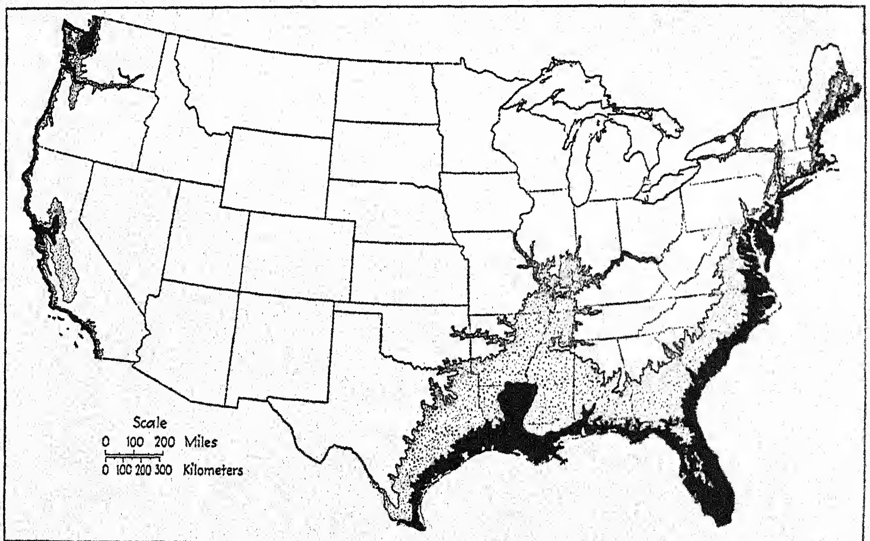


FIG. 184.—Map of United States showing areas (black) that would be submerged if land sank 100 feet; and areas (stippled) that would be submerged if land sank 500 feet.

the slope or gradient of the valleys; and (Fig. 183) the renewal of the work of producing an adjusted shore line following the submergence.

If the United States should sink 100 feet, the mouth of the Mississippi River would be above the city of Vicksburg, Mississippi, and a large area that is now along the river would thus be submerged (Fig. 184). If the downward movement should be 500 feet, a vast area (black and stippled areas in the figure) would be submerged. Valleys into which the sea has entered due to a sinking of the land are called *drowned valleys* (Fig. 182). Chesapeake Bay (a striking example) is the drowned lower portion of the Susquehanna River. The Potomac, Rappahannock, and James Rivers, which were formerly tributaries of the Susquehanna, also

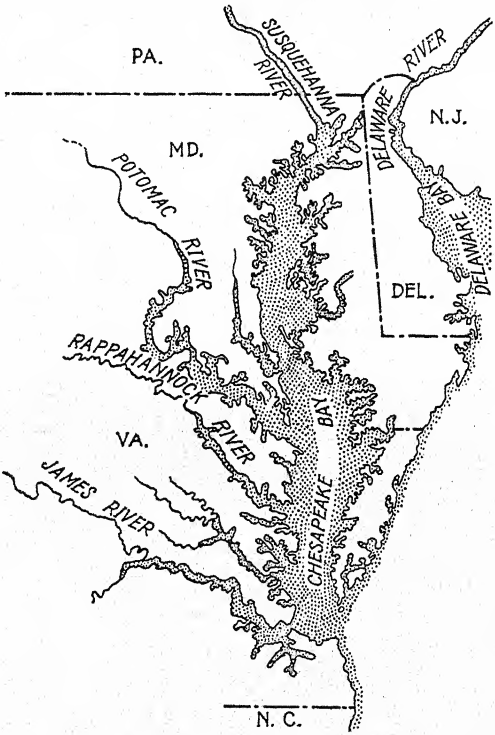


FIG. 185.—Drowned valleys on Atlantic coast.

have drowned valleys in their lower courses (Fig. 185). Delaware Bay is the drowned end of the Delaware River. The lower end of the Hudson River was also drowned; in fact the course of the Hudson can be traced on the sea floor for about 50 miles out to the edge of the continental shelf (Fig. 186). The outer part of this valley is a canyon about 2,400 feet deep and 3 miles wide.

Other lines of evidence of sinking shore lines are known. Buried fresh-water trees and sod have been found in the sea along the New Jersey coast and elsewhere. Man-made structures have sunk beneath the sea, and some, as the famous temple of Serapis at Pozzuoli, Italy, have been reelevated.

The result of a sinking coast is therefore to develop a shore line of numerous irregularities; hence the waves and currents must begin anew their work of adjusting the shore line. Projecting land masses must again be cut away and indentations filled out. Sinking of coasts and the consequent changes are going on constantly. The Atlantic seaboard in America is evidently sinking at present, but so slowly that it can only be detected by careful observations extending over a long period of years.

Effect of a Rising Coast.—The effect of a rising coast is much different from that of one that is sinking. If the land is raised (or, as is more

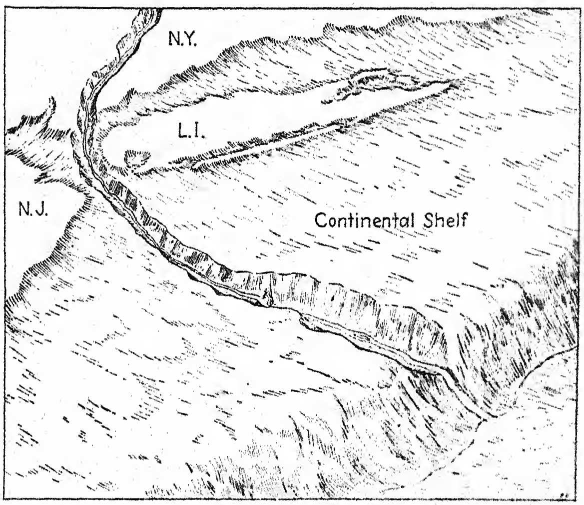


FIG. 186.—Sketch showing drowned course of the ancient Hudson River. Note deep canyon at lower end.

probable, the sea level goes down), the shore line is shifted seaward (see Fig. 94, page 92). The coast line formed by the emergence will be smoother than the old one because the deposition of material that had been going on offshore would, in varying degrees, have filled up the low places and left a smooth, uniform bottom. The important point about the outward shift of the seashore is that it would stop the work of adjustment that was going on at the higher level and start it anew at a lower level. The amount of work necessary to bring about adjustment would, however, be much less on the fairly smooth emerged coast than on the deeply indented shore resulting from a submergence of the land.

Evidences that the land has been raised are readily discernible along many sea coasts. The coast of California from Oceanside (below Los Angeles) to San Diego and beyond is a good example. The raised beaches, spits, hooks, bars, and sea cliffs in this section all show that the coast has gone up. Wave-cut terraces or beaches are common along the Alaska coast, and in some of those at Nome, Alaska, gold

placers were found. One of these gold-bearing beaches is 22 feet above the present sea level, the next is 38 feet above, and the highest is 78 feet.

The presence of wave-cut and wave-built terraces (Fig. 187) in the hills and mountains around Great Salt Lake shows that the water of the lake once stood much higher than it does today. These features show the evidences of wave action, just as it is seen today along seashores where wave-cut and wave-built terraces are being formed. The beaches or terraces were abandoned by the waves as the water in the lake evaporated. The succession of terraces shows that during periods of a fairly

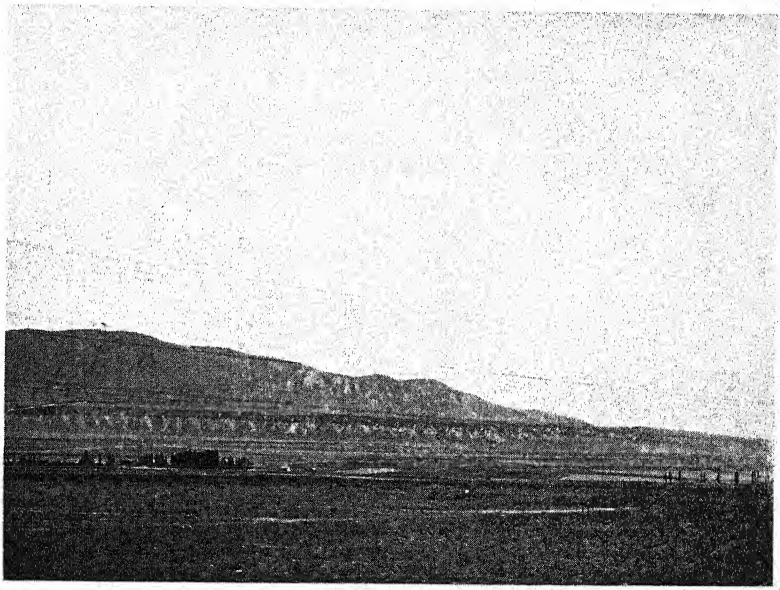


FIG. 187.—Wave-built terrace formed along the old shore line of Great Salt Lake. (*Photograph by W. A. Tarr.*)

stationary water level, due to the inflow's equaling the evaporation, the waves were able to build new beaches and terraces.

Modification of a Shore Line by Ice and Streams.—Wherever the edge of the great continental *ice sheets* reached the sea in a region of considerable relief, the glaciers dug out the bottoms of the stream-made valleys and steepened their sides. When the ice melted, a very irregular shore line of innumerable rocky headlands and many deep indentations was exposed. Moreover, as this type of irregular shore line developed best in fairly resistant rocks, a maximum amount of work for the waves and currents was produced, and thus the time necessary for the creation of an adjusted shore line was greatly lengthened. The deep, steep-sided valleys produced by the ice are known as *fiords*. The coasts of Sweden, Norway, and Alaska show large numbers of such features. The coast line of Maine is remarkable in being over 3,000 miles long (due to its

hundreds of bays and islands), though the direct line along the coast is only about 300 miles. This very irregular shore line was produced by the sinking of the shore in connection with the effect of ice on a stream-made topography. The waves have had very little effect on the rocks of this shore since the ice retreated.

Streams may produce irregularities in a shore line, or may make it straighter. A stream that is bringing more material to the ocean than the currents can move away builds a delta at its mouth, and so an irregularity in the shore line is produced. On the whole, however, the effect of streams is to produce a smoother shore line, for more of the material they contribute to the sea is used to fill up indentations than is used in the formation of deltas.

Summary.—The shape of any shore line is due primarily to the work of the waves and currents which are endeavoring to straighten it by cutting away the headlands and filling out the indentations. This process is interrupted, from time to time, by downward or upward movements of the shore, and is modified by the work of other physical agents, especially ice and streams. Allowing the agents of the ocean time enough, they will finally smooth out the irregularities of the coast and produce an adjusted shore line along which the work of erosion and deposition will be in balance.

MECHANICAL DEPOSITS IN THE OCEAN

No phase of the work of the ocean is more important than the formation of the large body of mechanically formed sediments that give rise to the three important *clastic rocks: conglomerates, sandstones*, and *shales.* Their formation will not be discussed here, however, as it is treated fully in the chapter on sedimentary rocks.

DEEP-SEA DEPOSITS

The deposits being made at present in the deep parts of the ocean have been studied in all parts of the world. They are called *muds, clays,* or *oozes,* and consist of materials from many sources. By far the larger part of the material is *volcanic dust and pumice, cosmic or meteoritic material,* and *organic material* (the hard parts of swimming creatures, as sharks' teeth and the ear bones of whales). Some of the material is derived from the land and is called *terrigenous.*

The *volcanic material* of deep-sea deposits may have been derived from land or island volcanoes, as well as from the submarine volcanoes. The fact that pumice will float for a long period of time would permit its journeying far from its source. Some material derived from *meteorites* has also been found in deep-sea deposits.

The *organic remains* found in deep-sea deposits are of various kinds, depending in part upon the depth of the water. Because calcium

carbonate is soluble in water, the calcareous shell of an organism will have largely disappeared before it sinks to a depth of 15,000 feet, and practically none of it will go below 20,000 feet. Below this depth, therefore, only the very insoluble parts of organisms occur. A single dredge of material from a depth of 14,300 feet contained 1,500 specimens of sharks' teeth and 50 ear bones of whales. Several kinds of "oozes" (as these deposits of organic remains are called) are distributed over the sea floor at varying depths. They are named from the dominant organism they contain. The common oozes, the depths at which they occur, and the area of the sea floor covered by them are given in the following table.

Deep-sea Oozes

Kinds	Average depth, feet	Area covered, square miles
Pteropod ooze	6,264	400.000
Diatom ooze	8,862	10,880,000
Globigerina ooze	12,294	49,520,000
Radiolarian ooze	17,364	2,290,000

Terrigenous material is more abundant in the parts nearer the continents, of course. This material has been carried out to the deep sea by floating ice that comes from the polar regions and from glaciers that reach the sea, as well as by wind and currents.

Red *clay*, which is the most insoluble of the deep-sea materials, is widely distributed over the sea floor, the estimated area covered by it being 51,500,000 square miles. Much if not most of the red clay is the result of the alteration of the other deep-sea materials. It occurs at depths ranging from 13,350 feet to the deepest parts of the ocean.

Some minor deep-sea deposits are found, of which the *manganese* and *phosphatic nodules* and a green mineral called *glauconite* are the most important.

The deep-sea deposits are meager, though they represent long periods of accumulation as shown by the relatively large number of sharks' teeth and other organic materials occurring in them. Very few if any of these deposits are found on the land.

CHEMICAL WORK OF THE OCEAN

The chemical work of the ocean is far less important than the mechanical work, as we have repeatedly noted. The chemical work includes *depositional work* and *solvent work.* Of the two the depositional work is by far the more important, consisting as it does in the formation of the

chemically formed sedimentary rocks: limestone, chert and *flint, salt,* and *gypsum.* The formation of these rocks, however, is discussed in the chapter on Sedimentary Rocks.

Solvent work, though of such minor importance, must be going on to some extent, as the water of the ocean is in constant contact with the materials along the shore. The finer fragments of these materials are undoubtedly altered, producing soluble substances of which some are soon deposited and others remain in solution.

CHAPTER IX

SEDIMENTARY ROCKS

We are now to consider the formation of the sedimentary rocks. The word "sedimentary," coming from the Latin word *sedimentum* which means "settling," is applied to these rocks because during their formation the materials composing them settled to the bottom of a body of water. This process of accumulation can go on in any body of water (pond, lake, lagoon, or the ocean) just as long as material is supplied by the work of the wind, the streams, or the waves of the body of water itself. As originally used, the term "sedimentary rocks" designated those rocks composed of solid particles that could be seen settling in water. Later it was learned that some rocks were formed from material in solution in the sea water and these are now included with the sedimentary rocks. Further studies have shown that deposits made upon the land by the wind or ice and those made along rivers and in lakes belong to the sedimentary rocks, also. The great majority of all sedimentary rocks, however, were formed in the ocean or in bodies of water directly connected with it.

The sedimentary rocks are the most common rocks at the surface of the earth. They are estimated to cover 75 per cent of the land surface, which leaves only 25 per cent for the igneous and metamorphic rocks together. In point of abundance in the earth's crust, however, the sedimentary rocks are insignificant, comprising only 5 per cent. Thus it will be seen that they form only a very thin layer at the top of the crust, the other 95 per cent of which undoubtedly consists predominantly of igneous rocks, though to how great an extent the metamorphic rocks may be present it is impossible to say. The layer of sedimentary rocks on the earth's surface ranges in thickness from a little more than zero to 40,000 or 50,000 feet. We have good evidence for believing that at one time sedimentary rocks were much more extensive than they are at present. They probably covered nearly if not quite all of the other rocks of the crust, and therefore have been cut away in great quantities, exposing the igneous and metamorphic rocks below. This eroded sedimentary material has been redeposited elsewhere, in the same manner as materials derived from the weathering of the primary igneous rocks.

Since sedimentary rocks form so much of the land surface, they are utilized extensively by man for building and industrial purposes. Likewise, as they are now the chief rocks subjected to the agents of erosion,

they have been carved into innumerable shapes. Some of these eroded areas are strikingly beautiful, as Glacier National Park, Bryce Canyon, Utah (Fig. 188), and the Grand Canyon of the Colorado River (see Fig. 103, page 102). Aside from possessing elements of beauty and utility, however, the sedimentary rocks are of great importance in furnishing a record of past life and of the major physical events in the history of the earth. The life story is depicted in the fossils that are found in the rocks, as we shall see in studying historical geology in the second part of this book. Other features of the rocks, such as their composition, color, and position, furnish information concerning the climate of past times and the changes that have occurred in the earth's crust.

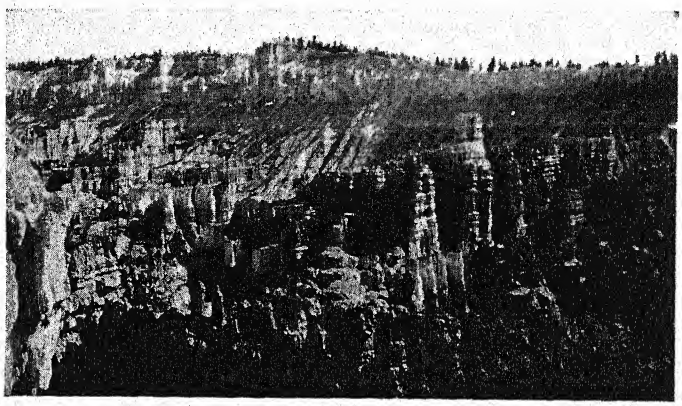


Fig. 188.—Bryce Canyon, Utah. (*Photograph by W. D. Keller.*)

The previous chapters on weathering, the work of the streams, and the ocean have amply prepared us for our present task. that of learning the details of the formation of the sedimentary rocks.

Source of the Materials in Sedimentary Rocks.—If we considered only the primary source of the materials in the sedimentary rocks, that source would be the igneous rocks; and during the formation of the first sedimentary rocks these *were* the only source. After some sedimentary rocks were formed, however, they also were exposed at the surface and weathered and so furnished material for other sediments. Rocks of the metamorphic group of rocks (Chap. X) that are formed from both igneous and sedimentary rocks are exposed at the surface, weathered, and so also furnish further sedimentary materials. Thus we see that all the different kinds of rocks, igneous, sedimentary, and metamorphic, have been sources of materials for the sedimentary rocks (see Fig. 244, page 222).

Kinds of Materials in Sedimentary Rocks.—The materials that go into the formation of the sedimentary rocks are readily divided into two groups: one consisting of *solid particles* and the other of *substances* carried

in solution. It will at once be recalled that the aim of the weathering process is twofold: to produce one group of substances that, because of their insolubility, necessarily consist of solid particles; and another group of soluble substances. Thus we see how directly the process of weathering is connected with the origin of sedimentary rocks. There is really a third kind of material (*i.e.*, *carbonaceous material* derived from the air) which enters sedimentary rocks. This material is very unimportant in amount and is wholly unrelated to the two large classes of materials.

The Clastic Materials.—The solid particles of which we have spoken are called *clastic materials* ("clastic" means "broken"). The term "fragmental" is also used but the other name is the more common one. An accumulation of these solid materials produces a clastic rock.

The size of the clastic materials is shown in the following table. These sizes are purely arbitrary but are the ones commonly accepted by geologists.

Size of Clastic Materials

Kinds	Diameter in Inches
Boulders	Over 8
Cobbles	2 to 8
Pebbles	3/8 to 2
Gravel	1/8 to 3/8
Sand	1/250 to 1/8
Silt	1/2500 to 1/250
Clay	Below 1/2500

Owing to this difference in size of the clastic materials they are sorted by the action of the waves and currents, and if the substances have about the same specific gravity particles of about the same size will be deposited together. If the substances differ in specific gravity, however, larger particles of the lighter materials will be mixed with smaller particles of the heavier materials. Thus hematite, an iron oxide, is nearly twice as heavy as quartz, and consequently smaller particles of hematite would be deposited with larger fragments of quartz.

As the currents move offshore into deeper water, their velocity is checked, which results in deposition of the materials they are carrying. The ideal sequence of this deposition would be first, and nearest the shore, the boulders, cobbles, and pebbles (these sizes are not commonly furnished by streams), next the gravels and sands, and lastly the silts and clays. In reality, of course, this sequence is subject to many variations, depending upon the strength of the currents, the supply of materials, and other factors.

The shape of the particles of clastic materials, which ranges from round to sharply angular (Fig. 189), is as variable as their size. Long-continued wear during transportation produces rounded particles even of very hard minerals. Thus certain sandstones, notably the St. Peter

sandstone found in Missouri and Illinois, consist of nearly perfectly rounded grains of quartz. Under ordinary conditions quartz grains are not rounded in water to sizes smaller than 0.75 millimeter in diameter

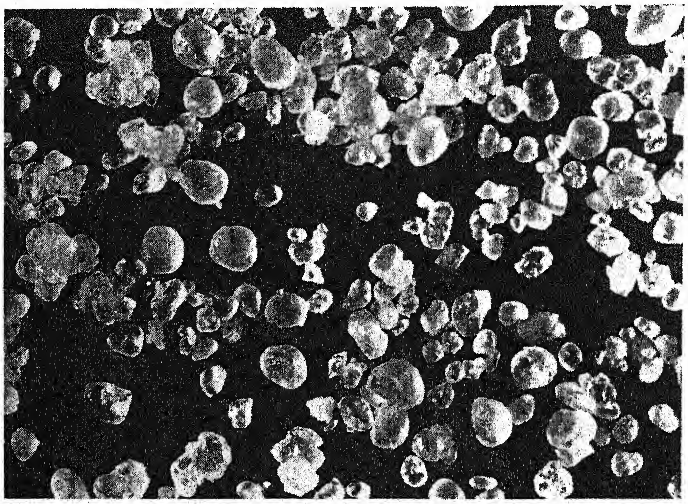


Fig. 189.—Rounded and angular grains of quartz sand. The very round grains are from the St. Peter sandstone. Twelve times natural size. (*Photograph furnished by Frank Conselman.*)

because the water around the grains breaks the blow. Wind can round grains much smaller. Rounded quartz grains have a dull appearance, known as a *mat surface*, owing to the fact that tiny chips have been

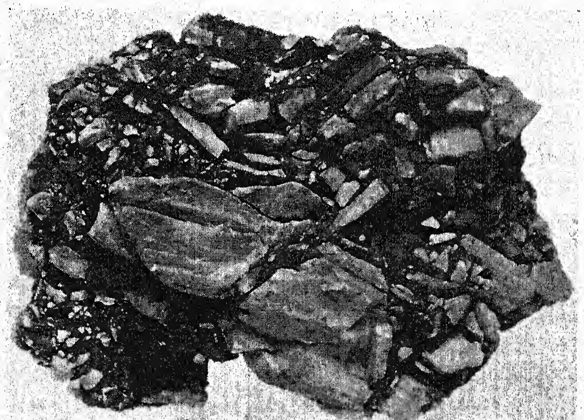


Fig. 190.—Breccia composed of chert fragments cemented with asphalt. One-fourth natural size.

broken off during rounding. A rock composed of sharp broken fragments, larger than sand particles, is called a "breccia" (Fig. 190). The material in such a rock had not been transported very far.

The clastic materials may be composed of any substance that can exist as solid particles. Fragments of all sorts of rocks, as granite, gabbro, felsite, slate, marble, sandstone, and coal, are found in them. Specimens of 20 different kinds of rocks have been recognized in Missouri River sand. The mineral particles found in the clastic rocks are more numerous than the rock particles. Clay minerals and quartz are overwhelmingly abundant among the minerals of certain clastic rocks, though the micas, feldspar, hornblende, and the iron oxides are also common in those rocks. Rare minerals of interest in clastic rocks are gold, platinum, and diamonds and other gems. Occasionally particles of calcite, gypsum, and dolomite (fairly soluble minerals) are found in clastic rocks.

The Soluble Materials.—The substances (aside from those present in mere traces) carried in solution to the ocean are comparatively few in contrast to the clastic materials. These substances are calcium, silica, sodium, magnesium, ferric and aluminum oxides, potassium, and the following radicals: carbonate (CO_3), sulfate (SO_4), chloride (Cl), and nitrate (NO_3). The table on page 150 in the preceding chapter should be consulted for the amounts of each of these substances added. The great abundance of the carbonate radical shows that about two-thirds (65 per cent) of the compounds are added to the sea as carbonates; the other third is transported as sulfates and chlorides. The silica and iron and aluminum oxides are transported as such. The iron and aluminum oxides (especially the latter) are not very soluble, hence are added to the sea only in small amounts. As we shall see later, some of these various substances are very soluble in the sea water and others are not.

The Carbonaceous Materials.—The carbonaceous materials are dominantly carbon compounds, as their name implies. The carbon for their formation is derived directly from the air and from the decay of organic compounds. Plants take carbon dioxide from the air, making use of the carbon in their cells and liberating most of the oxygen. The plants are then used as food by animals. Accumulations of carbonaceous materials from plants (and possibly animals) may under very special conditions become coal or oil. Swamps and lagoons along shore are ideal places for the accumulation to take place.

Where Sedimentary Materials Are Deposited.—The deposition of sedimentary materials may take place in all parts of the ocean, but actually most of the sedimentary rocks have been deposited in the shallower parts. At present this deposition is largely restricted to the 10,000,000 square miles of the epicontinental seas along the margins of the continents, but in past geologic periods, during which the ocean had submerged 50 per cent or more of the continents as they exist today, sediments were deposited far inland from what are now the shores of the ocean. As was noted in our study of the ocean, material is now accumulating in the deep seas, but these deposits apparently have no

counterpart in any of the sedimentary rocks. The kind and amount of sediments deposited in any one locality are controlled by the source of material, strength and direction of the waves and currents, depth of the water, and distance from the shore.

The sediments may be deposited adjacent to the shore and are then called *near-shore deposits*, or they may be carried variable distances out upon the continental shelf or beyond it and are then called *offshore deposits*. These terms are of value only as indicating the location of deposition, for all kinds and sizes of material may be deposited from the beach outward. An ideal outward sequence probably does not exist. At one point along a shore a sand may be deposited, while a few miles away along the same shore there may be a deposit of mud. It is possible, even, that calcareous muds may be deposited at the immediate shore, as they are being deposited at present along the coasts of Florida and the Bahamas. In general the finest clastic materials and the chemical (as well as some organic) materials are deposited at a distance from the shore. Limestones require clear water for deposition. Certain chemical deposits, as salt and gypsum, are formed only in restricted seas. Broad, shallow, interior seas have spread over the continents of the past, and it was in such seas that most of the sedimentary rocks were deposited rather than in narrow epicontinental seas such as those in which deposition is taking place at present. Some of the seas in the interior of North America were 2,000 miles across, though not very deep. In such seas muds could be carried hundreds of miles out from the land, and a single continuous deposit of sandstone, shale, or limestone might cover many thousand square miles.

CLASSIFICATION OF SEDIMENTARY ROCKS

Based upon their origin, the sedimentary rocks may be readily classified into three groups: *clastic sedimentary rocks, chemical sedimentary rocks*, and *organic sedimentary rocks*. These groups, arising as they do from the products of weathering, may be shown graphically (study carefully the chart on opposite page).

The Dominant Kinds of Sedimentary Rocks.—Though several kinds are given in the chart, a world-wide study of sedimentary rocks has shown that three kinds are most abundant. These are, in the order of their estimated abundance: *shales*, comprising 82 per cent of all sedimentary rocks; *sandstones*, 12 per cent; and *chalk, limestones*, and *dolomites*, 6 per cent (Fig. 191). In this grouping clays and siltstones are included with shales, conglomerates with sandstones, and chert and flint with the carbonate rocks. All the other kinds of rocks form but a small portion of the grand total. We must account for the greater abundance of these dominant rocks.

Sedimentary Rocks

Formed through weathering

- Mechanical weathering
  - Produces fragments of minerals and rocks that are
    - Removed mechanically and deposited as the
      - Clastic Sedimentary Rocks
        - Conglomerates, Breccias .... Boulders, Cobbles, Pebbles, Gravels
        - Sandstone .... Sand
        - Siltstone .... Silt
        - Shale .... Clay
- Chemical weathering
  - Produces insoluble products that are
    - Removed mechanically and deposited as the (Clastic Sedimentary Rocks)
  - Produces soluble products that are
    - Removed in solution by streams and deposited as the
      - Chemical Sedimentary Rocks
        - (The rocks formed from substances relatively insoluble in sea water, hence deposited soon after reaching the sea)
          - Limestone, Chalk .... $CaCO_3$
          - Dolomite .... $MgCO_3$, $CaCO_3$
          - Chert, Flint .... Colloidal silica
          - Hematite, Limonite .... Iron oxides
        - (The rocks formed from substances very soluble in sea water, hence deposited only as a result of evaporation)
          - (in order of deposition
          - Gypsum .... $CaSO_4.2H_2O$
          - Anhydrite .... $CaSO_4$
          - Salt (halite) ...... NaCl
          - Potassium and Magnesium minerals
      - Organic Sedimentary Rocks
        - Calcareous: Limestone
        - Siliceous: Diatomaceous earth
        - Carbonaceous: Coal, Oil, Natural gas

The great abundance of *shales* among sedimentary rocks is explained by the fact (as we saw under Weathering) that the dominant mineral in the average igneous rock is feldspar, which breaks down to various clay minerals, as do also other aluminum-bearing minerals in igneous rocks. Now shale is composed chiefly of clay minerals, and so, as they are the most abundant minerals formed during the weathering of igneous rocks, we see at once that shale *should* be the most abundant sedimentary rock.

Sandstones rank second in abundance because they consist dominantly of quartz, a very hard, insoluble mineral that forms about 12 per cent of the average igneous rock. The main loss of this quartz during weathering is by the abrasion of the grains, but on account of its extreme hardness even abrasion takes place very slowly.

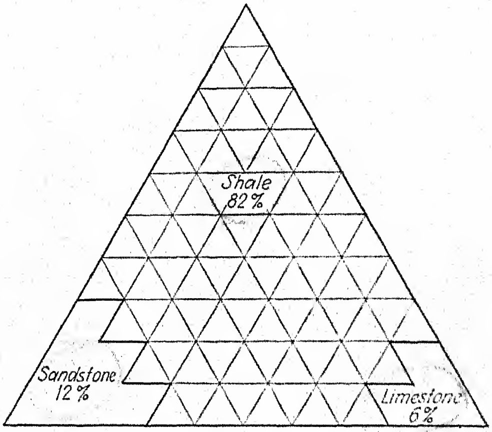


FIG. 191.—Diagram showing the percentages of each of the major classes of sedimentary rocks. Each small triangle equals one per cent.

The abundance of *chalk, limestone,* and *dolomite* is accounted for by the fact that calcium and magnesium carbonates are the most abundant substances of the soluble products of weathering, together with the fact that their insolubility in the sea water causes their early deposition. *Chert* and *flint* are very abundant in some of the carbonate rocks. We have noted in discussing the weathering of igneous rocks that, of the silica set free, a part was carried in solution to the sea, and it is a part of this silica that was deposited so abundantly as chert and flint.

Thus we see that the abundance of certain compounds in the original rocks leads during the weathering process to their concentration in other forms (the sedimentary rocks) at the surface.

The Gradations among Sedimentary Rocks.—The chart of the classification of sedimentary rocks given above shows at a glance where each of them belongs. Inasmuch as the deposition of the various sedimentary materials is taking place all the time in the waters surrounding the continents, a certain area may be receiving one kind of material, adjacent

areas very different kinds, and some areas none. The deposit at one place may consist essentially of one material, as a pure sand, clay, or limestone, but it is very evident that the deposition of any one material does not cease abruptly at a certain point and another type begin abruptly at that point. The deposition of clastic materials depends upon the velocity of the transporting agent. As this velocity gradually decreases, so also does the size of the particles deposited. Grains of a deposit of sand may therefore gradually change in size along the shore, grading into a coarser deposit in one direction (becoming a conglomerate) or into a finer deposit in the opposite direction (becoming a silt or even a shale). Seaward, the change is a decrease in size of particles (Fig. 192); sand would thus grade into a clay. However, the currents that are transporting materials are not uniform from day to day; hence there is inevitably some mingling of sizes. As a result sandstones may contain some clay and are called *shaly* or *argillaceous sandstones*, shales may contain sand and are called *sandy* or *arenaceous shales.* Such rocks are gradation products.

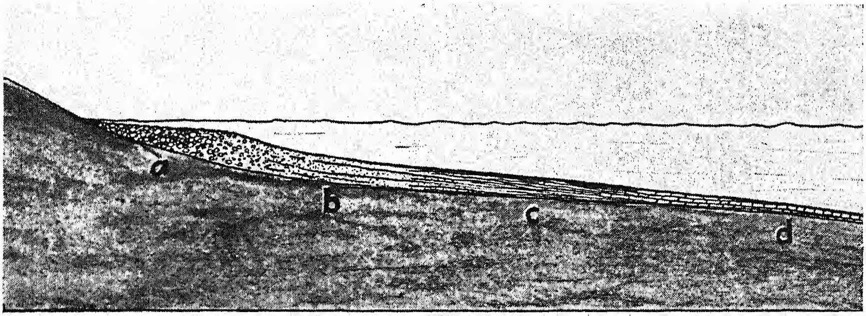


FIG. 192.—Lateral gradation of one sedimentary rock into another: (*a*) conglomerate into (*b*) sandstone into (*c*) shale into (*d*) limestone.

Gradations exist in chemical and organic rocks, also. The deposition of a limestone may be taking place (chemically or organically) adjacent to the deposition of clays or sands (Fig. 192), whereupon a zone of gradation will exist between the adjacent types of materials. As a result there are limestones that contain shale (*shaly limestones*) or sand (*sandy limestones*). This type of gradation results in a mixture of insoluble materials (the sand or clay) with those formed from materials (the calcium carbonate) in solution. These gradations are shown graphically in Fig. 193, which should be carefully studied.

The gradations just discussed are all lateral changes, but vertical gradations also exist. A sandstone may grade upward into a shale or a shale into a limestone. These changes are brought about in a number of ways, as will be shown more fully in the historical part of this volume. A gradual deepening of the water over a deposit of clastic materials would

result in the beginning of deposition of finer materials. So for a time fine and coarse particles would mingle, which would produce a gradational phase, as, for example, a sandstone that contained considerable clay. Or a gradual clearing of the water would start the deposition of some calcium carbonate along with the clay that had been going down, which would result in a gradational phase between a limestone and a shale. Other factors that would influence gradation of one material into another, not only vertically but also laterally, are changes in the distance of the deposition from shore, in the direction and strength of currents, and in the source and character of materials.

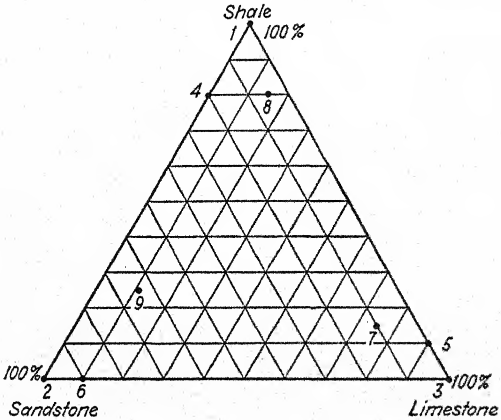


FIG. 193.—Diagram showing relationship of the three principal sediments. (1) 100 per cent shale; (2) 100 per cent sandstone; (3) 100 per cent limestone; (4) sandy shale (80 per cent shale and 20 per cent sand); (5) shaly limestone (90 per cent limestone and 10 per cent shale); (6) calcareous sandstone (90 per cent sandstone and 10 per cent limestone); (7) sandy, shaly limestone (75 per cent limestone, 15 per cent shale, and 10 per cent sand). Determine the rock names and the percentages of each constituent for (8) and (9).

It should be noted, however, that although gradations do exist the different sedimentary rocks are on the whole surprisingly pure. The vertical transition of one type of sedimentary rock into another is usually sharp and even the lateral change takes place in a surprisingly narrow gradational zone.

ORIGIN OF THE SEDIMENTARY ROCKS

The three principal methods by which the sedimentary rocks have originated have been indicated in the classification chart given on page 179. This chart shows a broad grouping of the rocks according to the present prevailing trend of thought, although there is no unanimous agreement among geologists as to the origin of all of the sedimentary rocks. We cannot go into great detail in this volume, but the broader outlines of the origin of the *clastic*, *chemical*, and *organic* sediments will be given.

The Origin of the Clastic Sedimentary Rocks

The clastic materials carried by streams, wind, and ocean currents are deposited whenever the velocity of the moving agent becomes insufficient to transport the particles farther. Deposition by streams and wind may occur on the land or in lakes, but such deposition is of minor importance so we shall discuss only the deposits made in the ocean.

Whatever the velocity of a river current may be, when the stream enters the quiet water of the ocean its velocity is checked and deposition takes place. The result of this deposition may be a delta, though most

FIG. 194.—Conglomerate south of Florence, Colorado. (*Photograph by W. A. Tarr.*)

of the material dropped will be immediately shifted by the waves and shore currents to quieter water along the shore or into deeper water offshore, the result in either case being deposition.

Formation of a Conglomerate.—The coarsest material being shifted by the waves is deposited along the beach, and if the size of the particles is above 3/8 inch in diameter (*i.e.*, pebble, cobble, and boulder sizes; see table, page 175) a conglomerate is formed (Fig. 194). A sea in encroaching upon the land may greatly widen the area of beach deposits so that a conglomerate bed of considerable extent will be formed.

Formation of a Sandstone.—The particles of the materials known as "gravel" and "sand" are smaller than 3/8 inch in diameter (see table, page 175) and hence are carried farther out than the coarse materials and eventually form beds of sandstone (Fig. 195). Though these materials may be carried offshore for miles, most sandstones are formed near shore. The thickness of the deposit will vary with the supply of sand, the strength of the currents, and the slope and configuration of the shore line.

Sandstones are made use of for building purposes wherever they occur. Many of them furnish very attractive stones.

Formation of Siltstones and Shale.—The finest particles (diameters below 1/250 inch), those of silt and clay, are carried the farthest and are deposited in the quiet waters beyond the reach of the waves and strong shore currents. However, if the land adjacent to a shore is low lying and the water shallow, silt and clay may be deposited up to the shore. These silts and clays become siltstones and shales after further consolidation. As silt particles are intermediate in size between those of sand and of clay (see table, page 175), siltstone forms a gradational phase between a sandstone and a shale. Siltstones are really quite abundant, though they are generally designated as shales. Probably 10 per cent of the total 82 per cent of shales consists of siltstone. Lagoons are the seat of the deposition of much of these fine materials. When exceptional floods or storms occur, coarser materials may be carried much farther out than is normal and thus a bed of sand may be deposited over a layer of clay. When normal conditions are restored, clay is deposited over the sand. In this way interbedded sandstones and shales are formed. Fine clays settle faster in the sea water than in fresh water, due to their having been coagulated into larger particles by the action of the salts in the sea. This fact would thus favor deposition nearer shore in sea water than in lakes.

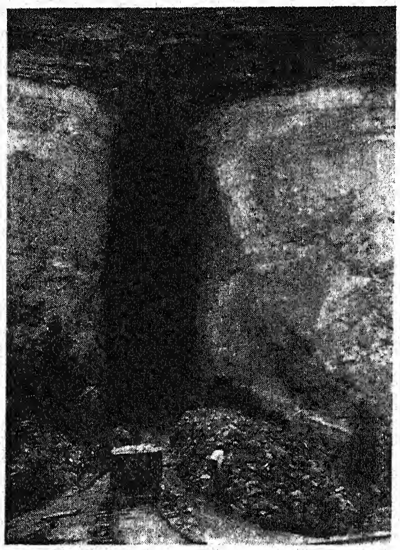


Fig. 195.—Thick bed of St. Peter sandstone at mine entrance, Pacific, Missouri. This sandstone is being mined for use in making glass. (*Photograph by W. A. Tarr.*)

On account of the great abundance of shale at the earth's surface man has adapted the rock to many uses. In the manufacture of brick, tile, and other clay products shale is widely used, and much of it is used also in making Portland cement.

Summary.—The deposition of the materials of the clastic rocks is due primarily to a decrease in the velocity of the transporting agent. The particles being transported are sorted; the larger and heavier ones are deposited first and then those of the successively smaller sizes down to the finest clay particles.

Origin of the Chemical Sedimentary Rocks

The sedimentary rocks formed by the precipitation of the soluble substances brought to the sea comprise one of the most interesting groups

of rocks. Most of them, such as limestone, salt, gypsum, and iron minerals, are extensively used by man. On the whole the origin of the rocks of this group is well understood, though much research is still needed to make clear many of the details of the methods of origin.

The soluble substances carried to the sea may be placed in two groups: one comprising those substances that are insoluble in the sea water and thus are rapidly deposited, and the other comprising those very soluble substances that accumulate in the sea water and are precipitated only under special conditions. The substances in these two groups are given in the lists below.

Substances Insoluble in Sea Water and Thus Quickly Precipitated	Very Soluble Substances Accumulating in Sea Water
Calcium carbonate	Sodium chloride
Magnesium carbonate	Calcium sulfate
Colloidal silica	Magnesium sulfate
Iron minerals	Magnesium chloride
	Potassium sulfate
	Potassium chloride

Substances Insoluble in Sea Water.—The materials that are rapidly removed from the sea water are the most abundant of the soluble substances carried to the sea annually.

Calcium Carbonate and the Rocks It Forms.—Calcium carbonate is the most abundant of all the soluble compounds added annually to the sea, yet there is essentially none of it in the sea water, which shows that it is rapidly removed. The removal is accomplished in two ways, chemically and organically (discussed later). At one time in the earth's history one of these methods of the formation of limestone has, on account of the existing conditions, been the predominant method, and at another period, another one.

It has been found experimentally that any process that removes carbon dioxide from the sea water, such as a rise in temperature, causes the chemical precipitation of the calcium carbonate (*calcite*). Upon its precipitation, the calcite settles to the sea floor as an extremely fine-grained mud. While the rock that results from this deposition is still soft and porous, it is known as *chalk* (if it contains much clay, it is called *marl*); later, through consolidation, it becomes a hard, firm *limestone*, which though fine grained may later become coarse grained through crystallization. These chemically precipitated limestones may contain some fossils, for the abundance of calcium carbonate in the sea water would be a favorable environment for those organisms that make use of calcium carbonate in their shells. The shells of the organisms accumulate, of course, along with the chemically precipitated calcium carbonate. Not uncommonly as the calcium carbonate is being deposited it forms small rounded grains known as *oolites.* These are really tiny concre-

tions. The floor of the bathing beach at Great Salt Lake is composed of such oolites (Fig. 196). A limestone composed of these grains is known as an *oolitic limestone.*

Magnesium Carbonate and the Rock It Forms.—The magnesium carbonate that is added to the sea water is not removed so fast as the calcium carbonate, as some of it is changed into the soluble magnesium sulfate and chloride and so accumulates in the water. A part of the magnesium carbonate, however, unites with the calcium carbonate that has been precipitated upon the sea floor and forms *dolomite* ($CaCO_3.MgCO_3$). Dolomite is as common as limestone among the older geologic formations. The two rocks resemble each other so closely that most people call both "limestone." Dolomite, however, is harder and heavier than limestone, but the best way to distinguish between them is by the hydrochloric acid test. Limestone dissolves rapidly (fizzes) in the acid, and dolomite, unless in a very fine powder, is scarcely affected. Many dolomites are unfossiliferous, but some contain a few fossils, usually in a poor state of preservation.

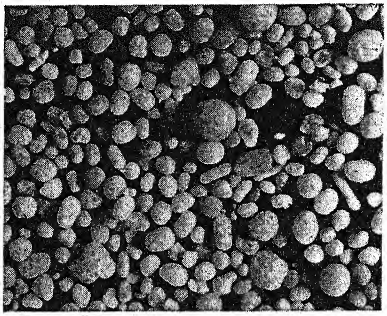


FIG. 196.—Oolites from Great Salt Lake. Enlarged six times.

Colloidal Silica and Its Resultant Rocks.—The second most abundant soluble substance added to the sea water annually by the rivers is colloidal silica, which constitutes 11.67 per cent of these materials. As sea water contains less than two parts of silica per million parts of water, it is evident that practically all of this silica is deposited. In contrast to the prevalent use of calcium carbonate made by animals in the construction of their hard parts, very few organisms of the sea make such use of silica. The larger part of the silica is therefore chemically precipitated. If streams are bringing clay to the ocean, much if not most of the silica is also deposited with the clay (it is a partial cause of the stickiness of clays). If the river waters are clear (carrying only materials in solution), however, the silica brought into the sea accumulates until it reaches the saturation point, whereupon the salts in the sea water cause its precipitation on the sea floor in the form of a colloidal or jelly-like mass containing water. The masses are rounded (Fig. 197, *a*); or, if the amount of silica precipitated is large, it is spread out on the floor as a lens (Figs. 197, *b*; and 198) or a bed (Fig. 199). As other sediments (chiefly limestone or chalk) are usually deposited over the rounded masses while they are still soft, they are flattened, though some masses become hard before burial and so retain their original shape. The hardened masses are called *nodules* or *concretions*, and *lenses* (Figs. 197,

c and *d*; and 198). Precipitated colloidal silica thus gives rise to the very abundant and widely occurring white *chert* (Fig. 198), and black *flint* (both are varieties of quartz) of limestone, chalk (Fig. 200), and dolomite. The association of chert and flint (both most commonly in the form of

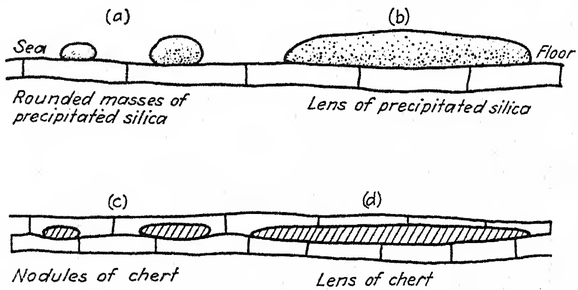


FIG. 197.—Sketch showing masses of silica precipitated on sea floor, and resulting chert after burial.

nodules) with calcareous deposits is just what would be expected, for both silica and calcium carbonate require clear water for their deposition. The occurrence of chert and flint with calcareous rocks is always with the purest forms of those rocks; for, if enough clay were present to form

FIG. 198.—Nodules and lenses of chert (light gray) in Burlington limestone, Columbia, Missouri. (*Photograph by W. A. Tarr.*)

a shaly limestone, for example, the silica would go down with the clay, leaving none for the formation of chert and flint. Chert and flint may contain calcareous fossils that became enclosed in them while the silica mass was soft. Such fossils are usually very well preserved, as the

silica gel protected them from destroying agents. Some of these fossils have later been changed to quartz by silica replacement.

Because chert and flint break readily into chips with sharp cutting edges, they have been used by man since the time of the stone ages, first

FIG. 199.—Chert bed (back of note book) in Cretaceous limestone, Tivoli, Italy. (*Photograph by W. A. Tarr.*)

as tools and later as a means of lighting fires. They may even be used for building materials, as shown in the accompanying picture (Fig. 201) of a church constructed of flint nodules.

Iron Minerals.—Only a very small quantity of iron is carried to the sea annually, due to the insolubility of the iron minerals. An abundance of decaying organic matter in the presence of these minerals, however, favors their solution. Some of the iron is removed as ferric oxide (Fe_2O_3) and a smaller quantity as ferrous carbonate ($FeCO_3$); for, though the carbonate is the more soluble, if oxygen enters the solution (as it commonly does) the iron will be oxidized to the ferric oxide, which is deposited at once on reaching the sea. Rarely, the conditions of solution on the land favor the removal of iron in quantities sufficient to form a bed of *hematite* or *limonite*, or very rarely of *siderite* (the carbonate). Hematite not uncommonly has replaced the calcium carbonate of shells on the sea floor and the bed of iron ore thus contains fossils. Calcareous oolites are also replaced by iron oxides, or the iron mineral may assume the oolitic form as it is deposited. The world's

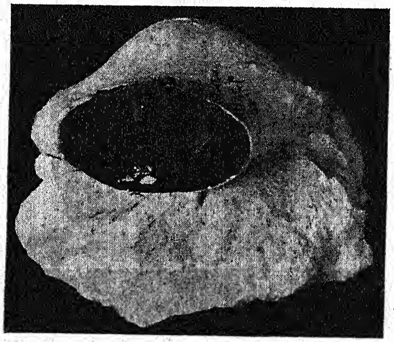


FIG. 200.—Flint nodule in the chalk, South Coulson, Surrey, England. Note the thin white coating of nodule. (*Photograph by W. A. Tarr.*)

most important supplies of iron ore come from sedimentary deposits. Notable deposits are those of the Lake Superior region (Fig. 202), the Clinton iron ore of the Appalachian region, the Lorraine iron ores of France and Germany, and (probably) the great Brazilian iron deposits.

Substances Soluble in Sea Water.—In discussing the soluble mineral content of the sea water (page 150) we found that *sodium chloride* (77.8 per cent), *magnesium chloride* (10.9 per cent), *magnesium sulfate* (4.7 per cent), *calcium sulfate* (3.6 per cent), and *potassium sulfate* (2.5 per cent) are present. The fact that the present sea water contains these compounds in large amounts is evidence of their great solubility. These substances continue to accumulate until special conditions make possible their precipitation.

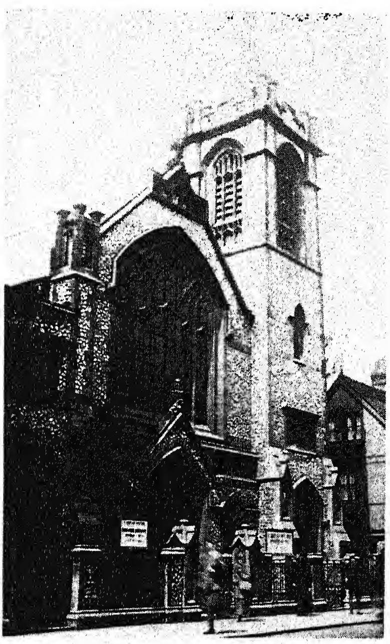


Fig. 201.—Church constructed of flint nodules, Cambridge, England. (*Photograph by W. A. Tarr.*)

Fig. 202.—Iron ore from Lake Superior district. Light bands are hematite. Dark bands are jasper (chert containing hematite). One-fourth natural size.

Sodium Chloride and Its Deposits.—Sodium chloride has apparently been accumulating in the sea water since the beginning of the ocean. From time to time during the past, *salt* has been deposited, but the total quantity thus removed is only a small fraction of what is still in the sea Salt is so soluble in water that the only common way of removing it is to evaporate the water, and even then it is not deposited until nearly 90 per cent of the water has been removed. The deposits of salt show that they were formed in an isolated body of sea water which evaporated until deposition took place. The evaporating body of water could be a bay or inland sea, and it might even be so closely connected with the main body of water as to receive influxes of sea water during storms. These influxes of fresher water would stop deposition until evaporation

had again concentrated the water, but they would add to the total amount of salt present. The salt is deposited in beds that for the most part are only 10 to 30 feet thick, but rarely are 400 feet thick. It is possible also that the waters of lakes could evaporate until they became so saturated with salt that it would be deposited. Figure 203 shows salt in a dried-up lake or playa in north-central Nevada. Such salt deposits are common in shallow lakes that dry up during a part of a year. If Great Salt Lake were to evaporate, it is estimated that it would deposit 400,000,000 tons of salt.

Calcium Sulfate and the Rocks It Forms.—Calcium sulfate is not so soluble in water as sodium chloride; therefore, as a body of sea water

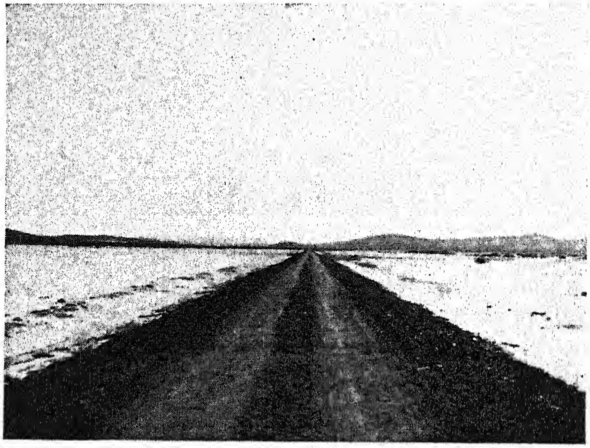


Fig. 203.—Salt plain in central Nevada. (*Photograph by W. A. Tarr.*)

evaporates, *gypsum*, the rock which calcium sulfate forms, is deposited before salt. Calcium sulfate forms two different deposits: one, the common gypsum ($CaSO_4.2H_2O$), and the other, *anhydrite* ($CaSO_4$). Though both are known to be deposited as sea water evaporates, gypsum is much more common. Gypsum occurs in three forms: a fine-grained massive rock, *alabaster;* transparent crystals, many two feet long, *selenite;* and a fibrous aggregate, *satinspar* (Fig. 204). The occurrence of pure gypsum in beds of widespread extent has led to the conclusion that the process of its concentration must have been repeated, some evaporation having occurred in a shallow basin from which the water flowed to another basin where it was further evaporated until finally gypsum was deposited in a very pure form.

Deposits of gypsum are usually associated with those of salt, but not always. Gypsum occurs abundantly in the red beds of western United States. It is used for making wall plasters and plaster of Paris.

Magnesium and Potassium Sulfates and Chlorides.—The most soluble of all substances in sea water are the magnesium and potassium sulfates

and chlorides; hence they remain in solution after all the other substances are deposited, and their deposition occurs only after all the water is evaporated. The final concentrated solution from which they are deposited is known as the *bittern*. It is an interesting fact that potassium is present in the original rocks in an amount only slightly less than that of sodium, yet in the sea water it is only about one-thirtieth as abundant. This is explained by the fact (already mentioned under Weathering) that most of the potassium is sorbed by the clay particles and therefore remains in the soil or goes into the formation of shales.

Apparently the complete evaporation of a body of sea water has occurred only a few times in the earth's history and then very locally.

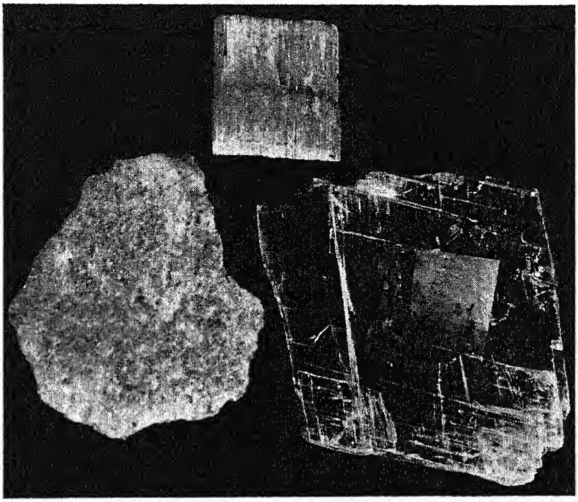


Fig. 204.—The three common varieties of gypsum. Satinspar (at top); alabaster (left); selenite (right).

The world's largest deposits of potassium and magnesium salts are at Stassfurt, Germany. The world markets for them are controlled by the Germans. A smaller deposit occurs in France but there is a working agreement between the two countries as to the price of the salts. Recent explorations in western Texas and eastern New Mexico have shown the presence of potassium salts, but the importance of the deposits has yet to be proved. Potassium salts are more important commercially than those of magnesium on account of their extensive use as a fertilizer.

Summary.—As a body of sea water is evaporated, the first mineral to be deposited is gypsum, next salt, and lastly, with complete evaporation, the magnesium and potassium minerals.

Origin of the Organic Sedimentary Rocks

The third method by which sedimentary rocks are formed is through the life processes of certain organisms. Both animals and plants con-

tribute to the formation of these rocks. We shall discuss the organic sediments, however, according to the kind of material deposited, *i.e.*, *calcareous*, *siliceous*, and *carbonaceous*. One of these groups, the carbonaceous, furnishes a material that has proved to be indispensable in modern civilization.

Calcareous Deposits.—Organisms play a very important part in the origin of some limestones. A vast number of creatures living in the ocean (and fresh waters, also) build their hard parts out of calcium carbonate. One has only to note the large number of shells along a sea shore to realize the abundance of such forms. These creatures are probably removing the larger part of the calcium carbonate added to the sea annually. Where the temperature, clearness of the water, and food supply are suitable, they live in vast numbers (as do the corals about

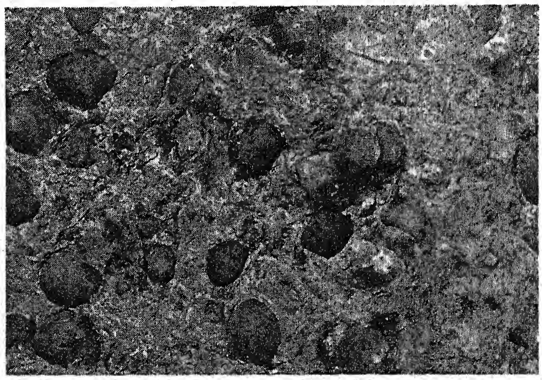


FIG. 205.—Fossiliferous limestone. Slightly reduced.

some islands and along some continents). When these organisms die, their hard parts remain and eventually accumulate in sufficient amounts to form a bed or layer. If wave action is considerable, the shells may be broken up, forming a calcareous gravel, sand, or mud. These accumulated materials become *limestone.* If all the shells are completely broken up and pulverized, the limestone will not show fossils, but usually, fossils are more or less abundant in organic limestones (Fig. 205). Unless a limestone consists predominantly of fossils, it is not possible, by any physical methods yet known, to distinguish with certainty between an organic and a chemically precipitated limestone, as the latter may very possibly contain some fossils, also. Texture, mode of occurrence, and associated rocks are the criteria used at present in deciding between them. Chalk has always been regarded as an accumulation of the shells of minute organisms but recent studies have shown that only a small percentage of the rock consists of organic remains, the major part being undoubtedly a chemical precipitate.

Various calcareous oozes are being deposited on the floor of the deep sea, at present, but these deposits have no counterparts in the rocks of the land.

Siliceous Deposits.—Deposits of siliceous organic remains are for the most part unimportant. Some deep-sea oozes are siliceous, but it is doubtful if such deposits occur on the land. The one siliceous deposit of any abundance is composed of diatom remains. Diatoms are small plants which use silica for their hard parts. Where they live abundantly in the sea water, thick beds of their remains may accumulate. Such deposits, called *diatomaceous earth,* are known in many parts of the world, but the largest are those of California, where beds hundreds of feet thick occur. Some men are of the opinion that the petroleum found in California was derived from these tiny organisms. Certain sponges have siliceous skeletons (the common household sponge is an example) but they do not accumulate in sufficient abundance to form beds.

Carbonaceous Deposits.—There are two important carbonaceous deposits: *coal* and *oil.* The former is wholly of vegetable origin but both plants and animals have probably contributed to the formation of the latter.

Formation of Coal.—Coal is the result of an accumulation of plant remains under such conditions that the plant tissues are converted into a deposit rich in carbon. The most favorable place for such a process is a swamp in which the vegetation grows abundantly and is submerged under water as it dies. Submergence prevents dry rot (seen in logs in forests), which completely destroys plant remains. The vegetation in the water undergoes a slow decay, and this process is aided by anaerobic bacteria that eliminate the oxygen and hydrogen of the plant tissues while concentrating the carbon. The material is then buried under other sediments and still further compressed and altered until it becomes a bed of coal. The kind of coal formed depends upon the character of the vegetation and the degree of its alteration in the swamp and after burial. Anthracite or hard coal has undergone the greatest changes.

Formation of Petroleum or Oil.—Oil, although a liquid, belongs in the group of sedimentary deposits. It is a very complex hydrocarbon and in the condition in which it comes from the ground consists of varying amounts of benzene, kerosene, gasoline, lubricating oils, paraffin, and asphalt. It is now generally believed that the origin of oil is organic and that both plants and animals have contributed to its formation. Just where all the changes that produced oil took place is not definitely known, but the following appear to be likely possibilities. (1) Oil drops may have been formed within the organism, been released upon its death, and then buried. (2) The oil may have been formed during the decay of the organism on the floor of the swamp, lagoon, or sea and then buried.

(3) Organic material may have been buried in the muds and after the burial been altered into oil. The formation of natural gas is largely due to subsequent reactions within the oil. After the oil was buried it migrated through the rocks and accumulated in large quantities in porous rocks (usually sandstone or channeled limestone) called *reservoirs*. The formation and accumulation of oil took place in deposits made along shores for it is there that the life was most abundant.

CONSOLIDATION OF SEDIMENTARY ROCKS

During our discussion of the origin of sedimentary rocks we have seen that the sediments are deposited as soft, loose materials. The materials composing prospective conglomerates and sandstones, for example, though packed closely by wave and current action, contain nothing between the grains to hold them together. The changes that convert the deposits of sediments into hard firm rocks are both *mechanical* and *chemical*. The methods of consolidation can be tabulated as follows:

Mechanical methods of consolidation.
- *a.* Pressure of overlying rocks.
- *b.* Drying of deposits.

Chemical methods of consolidation.
- *a.* Cementation by
  1. Calcium carbonate.
  2. Silica.
  3. Iron oxides.
- *b.* Crystallization.

Pressure.—Mechanical consolidation due to pressure takes place as more sediments are deposited above a given bed. The weight of the overlying deposits forces the particles of the bed below closer together (except in sandstones and conglomerates). This squeezing eliminates much of the water still present in the materials.

Drying.—The other mechanical method of consolidation is drying. As the rocks dry, the water that was not squeezed out by the pressure of beds above is eliminated. The deposit might thus become a porous rock unless further consolidated by pressure or other means of consolidation. Coal is a rock that has been both greatly compressed and dried, as many feet of plant remains are necessary for the formation of one foot of coal.

Cementation.—Cementation is a very important means of chemical consolidation, especially in the coarser clastic rocks, the conglomerates and sandstones, and more rarely in coarse accumulations of organic remains. These coarse-grained rocks are very porous and water circulates through them easily, as we have seen in studying ground water. If this water is carrying material in solution it may be deposited between the grains of the rock. The deposition of the material, or *cement* as it is

called, may be uniformly distributed through a rock, or it may take place only in certain parts where conditions for precipitation are most favorable. If the amount of the cement is small, it may be deposited locally, forming a concretion (see Fig. 128, page 128). The most common cements are *calcium carbonate*, *silica*, and the *iron oxides* (other materials occurring rarely). When the pores of a rock are filled with cement, circulation of water through it ceases. Deposition in rocks may occur from the surface downward; but, as we learned under Ground Water, it is especially common in the saturated zone below the water level (called the "zone of cementation" because of this fact).

Calcium Carbonate.—The most common cement in sedimentary rocks is calcium carbonate, as would be expected, for it is the most common mineral constituent of the average ground water. Some sandstones become completely cemented with calcium carbonate and so contain a high percentage of it.

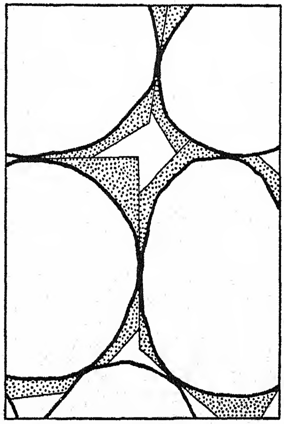


FIG. 206.—Diagram showing crystal faces (stippled) of quartz developed on rounded grains of sandstone during cementation.

Silica.—Silica also is a very common cement. It enters the rocks in the colloidal form and is deposited as quartz. Therefore, in a sandstone composed of grains of quartz that had been rounded by erosion, the grains may start to grow again; and, if there is not enough silica to fill up the interstices between them, crystal faces may develop on these rounded quartz grains (Fig. 206). These faces can be seen as tiny glistening points on the surface of a broken piece of sandstone.

A sandstone cemented with silica is known as *quartzite*. It can be distinguished from sandstone because it breaks *through* the grains, whereas a sandstone breaks *around* the grains. This is because the cement in a quartzite is as strong as the quartz grains and the break therefore goes evenly through both.

Iron Oxides.—The iron oxides hematite and limonite both occur as cements in sedimentary rocks, though less commonly than calcium carbonate and silica. Iron-bearing concretions are common.

Crystallization.—Crystallization is the chief means of consolidating the chemical sediments. Limestones, dolomites, chert and flint, and salt and gypsum all change from the very fine-grained rocks formed by precipitation into crystalline masses. In some rocks the change in size of the grains has been so insignificant that the crystals or grains cannot be distinguished even with a microscope. This is true for chert and flint, chalk, and some limestones. In other rocks the crystals are large,

producing coarse-grained rocks. Salt and gypsum may be very coarse grained. A bed of gypsum in western Oklahoma contains crystals six inches long (Fig. 207). The process of crystallization is simply the growth of the larger particles in a mass of fine material at the expense of the smaller particles. The small grains pass into solution in the water that is still in the rock faster than do the larger grains, and this material is redeposited upon the larger grains because, on account of their size, they have a greater ability to attract the material in solution. Thus the rock grows coarser in texture as long as solutions are present in the rocks.

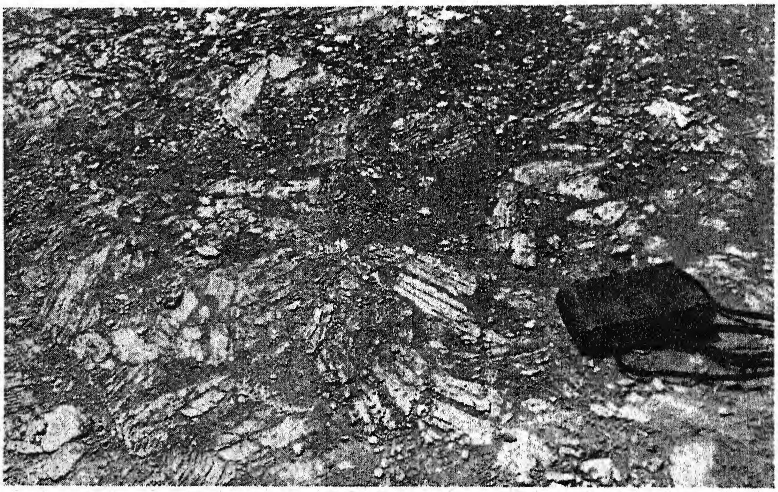


FIG. 207.—Bed of gypsum composed of large crystals of selenite, western Oklahoma. (*Photograph by W. A. Tarr.*)

FEATURES OF SEDIMENTARY ROCKS

Certain characteristic features are common to sedimentary rocks and thus are of assistance in identifying them. Most of these features were formed during the deposition of the sediments but others were formed subsequently. These features are as follows:

- Bedding
- Cross-bedding
- Ripple marks
  - Current
  - Wave
- Swash marks
- Rill marks
- Rain prints
- Mud cracks
- Fossils
- Oolites
- Concretions
- Stylolites
- Cone-in-cone
- Color

Bedding.—Sedimentary rocks are typically bedded deposits. During their formation they were spread out on the sea floor as sheets or layers

of variable lateral extent. Some beds are remarkably persistent, covering vast areas though not necessarily to the same thickness throughout;

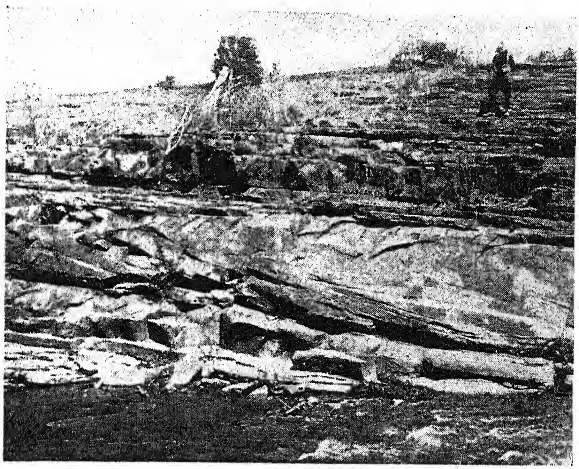


Fig. 208.—La Motte sandstone, Fredericktown, Missouri. Thick bed at bottom is cross-bedded. (*Photograph by W. A. Tarr.*)

others are merely local and may be measured in hundreds of square feet. The thickness of the beds ranges from less than that of a sheet of paper to

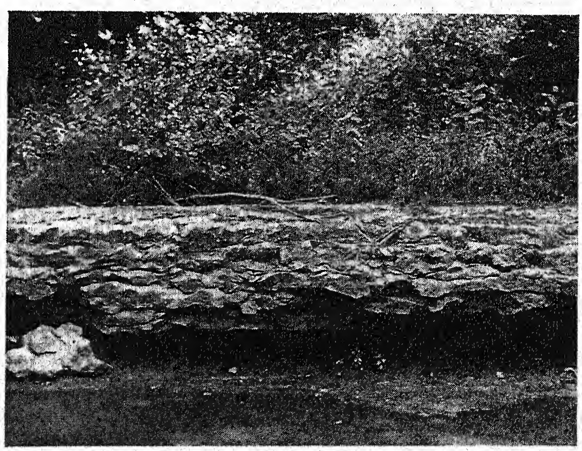


Fig. 209.—Nodular bedding in limestone, Boone County, Missouri. (*Photograph by W. A. Tarr.*)

10 and, rarely, more than 100 feet. The vast majority of beds are from a few inches (Fig. 208) to a few feet in thickness (Fig. 208). The very thin beds are called *laminae* (see Fig. 142, page 135). The top and bottom of a bed are normally nearly parallel, though some bedding is so uneven as to give rise to so-called *nodular bedding* (Fig. 209)

The bedding in rocks is due: (1) *to differences in the kinds of material deposited,* as would exist between a bed of shale and a bed of limestone; (2) *to differences in the sizes of the particles deposited,* as those existing

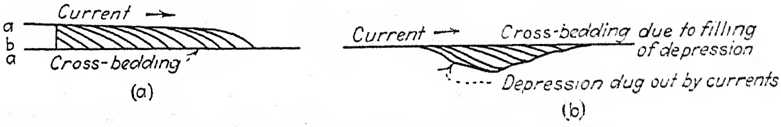


FIG. 210.—Sketch showing development of cross-bedding.

between layers of coarse- and fine-grained sandstone; or (3) *to variations in the color of the materials deposited,* as those between light- and dark-gray layers of limestone.

Cross-bedding.—Normally the bedding of sediments is essentially parallel but in the coarser clastic sediments two sets of bedding planes are not uncommon. In Fig. 210 at (*a*), *a* and *a* represent the normal

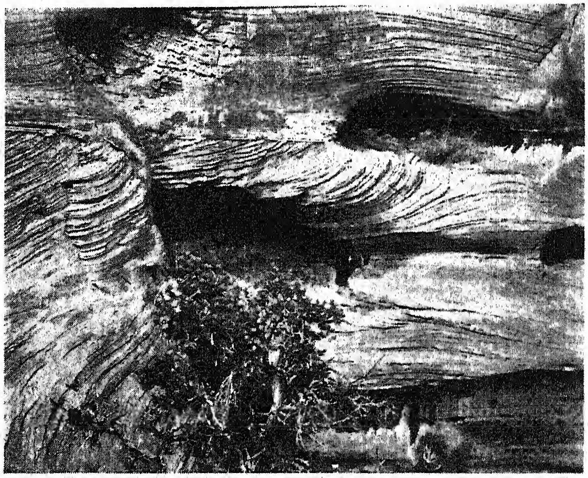


FIG. 211.—Cross-bedding in the Moenkopi sandstone, Canyon de Chelly, Arizona. (*Photograph by E. B. Branson.*)

bedding planes, and *b* the shorter bedding planes that cross from *a* to *a*. A rock bedded in this manner is said to be *cross-bedded.* Cross-bedding is developed in a deposit when the currents forming it are strong and frequently change direction. Thus at (*a*) of Fig. 210 strong currents have carried material rapidly offshore, producing a cross-bedded layer having a steep front. Also, strong currents created by storms may scour out depressions in the sea floor, which, as the currents lose their velocity and begin to deposit, are filled up, producing cross-bedding (Fig. 210, (*b*). Not uncommonly the cross-bedding between successive layers lies at different angles, due to changes in the direction of the

current producing it. Cross-bedding is most common in sandstones (Figs. 208 and 211) but is seen in some limestones, also.

Ripple Marks.—As the currents move over the sea bottom, they shift the particles along with them. If most of the material is rolled along, variations in the size of the grains will cause some particles to move faster than others and thus a depression at right angles to the current will be developed between the faster moving particles and those lagging behind. These depressions will be rapidly deepened, and soon

FIG. 212.—Current ripple marks in the St. Peter sandstone, Missouri. Which way was the current moving?

the surface will be covered with a series of roughly parallel depressions and the intervening ridges. Such a surface is *ripple marked.* Ripple marks are formed very commonly wherever moving water has clastic materials to work upon. The ripple marks differ in size, but in sands of medium-sized grain they are commonly ¾ inch to 2 inches from crest to crest. Rarely, the distance from crest to crest may be several inches. There are two common types of ripple marks: *current* and *wave.*

Current ripple marks may be made either by a current of water (Fig. 212) or by wind (Fig. 280, page 256), although those made by the latter agent are rarely ever preserved in sedimentary rocks. In cross-section, current ripple marks have the typical shape shown at *a* in Fig. 213. To produce the ripple mark of the figure the current must be moving to the right. The material is dragged up the gentle slope and rolled down the steep slope, and thus the ripple mark advances to the right.

Wave ripple marks are produced by the up-and-down movement of the water caused by a wave along a shore. Wind does not make wave

ripple marks. The two sides of a wave ripple mark have similar slopes (Fig. 213-*b*) and the ridges are sharp, although when these features are found preserved in the rocks the sharp crests have usually been cut off by later movements of the water.

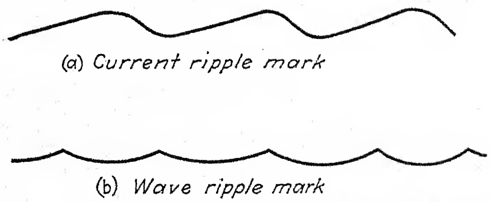


FIG. 213.—Diagram of current and wave ripple marks.

Swash Marks.—Swash marks are formed by waves along a beach (Fig. 214). A mark is formed at the highest point reached by each wave as it runs up the beach, and a following wave destroys at least a part of the mark made by the preceding wave. These marks are sometimes buried and preserved in the rocks.

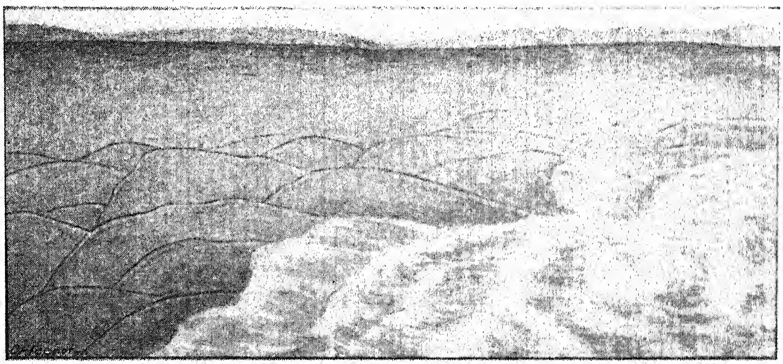


FIG. 214.—Sketch of swash marks on a beach.

Rill Marks.—Rill marks are depressions scoured out by water that runs back down the beach after the breaking of a wave. If the depressions that are made are filled by sand before the next high tide, they may be preserved in a future sedimentary rock.

Rain Prints.—Raindrops that fall on fairly firm silts and muds form impressions, which, if preserved, become features of sedimentary rocks (Fig. 215).

Mud Cracks and Mud Curls.—Mud cracks and mud curls (Fig. 215) are formed as a result of the drying of an exposed deposit of clay, silt, or sand. Many cracks thus formed extend downward for two feet or more, especially in the silts and muds along rivers (Fig. 216). Cracks

along rivers eventually become covered with water and filled with other material (Fig. 217) which preserves them if the deposit is buried. Broad mud flats along the seashore that are submerged only during storms at

FIG. 215.—Rain prints, mud curls, and mud cracks in clay, Versailles, Missouri. (*Photograph by W. A. Tarr.*)

FIG. 216.—Cracks in mud flats along the Missouri River, central Missouri. Size seen by hammer at left. Some of these cracks were two feet deep. (*Photograph by W. A. Tarr.*)

high tide are favorable places for the development of mud cracks and also for their preservation as features of sedimentary rocks. Mud curls develop in laminated muds. They are caused by the faster drying of

the surface of a layer, which therefore shrinks more than the lower part and so curls upward (Fig. 215).

Fossils.—The presence in a rock of fossils of any sort, such as shells, bones, teeth, and the imprints of tracks, can safely be interpreted as indicating a sedimentary rock. A few occurrences of fossils in tuff beds

FIG. 217.—Fossil mud cracks near Pennington Gap, Virginia. (*Photograph by W. A. Tarr.*)

are known, but it is easy to prove the volcanic origin of such beds. These beds were formed by the falling of the volcanic dust into a body of water containing animals and plants, which were thus incorporated with the volcanic material.

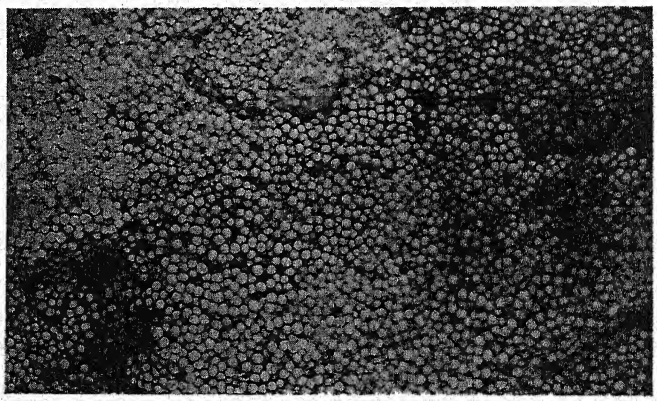


FIG. 218.—Siliceous oolite (natural size) from Washington County, Missouri.

Oolites.—Oolites are distinctive features of sedimentary rocks, but they have already been described as small calcareous concretions which may form during the deposition of calcium carbonate. The calcium

carbonate of the oolite may be replaced by silica and form siliceous oolites (Fig. 218).

Concretions.—Concretions are common features of sedimentary rocks. We have already discussed (page 130) those concretions that are formed

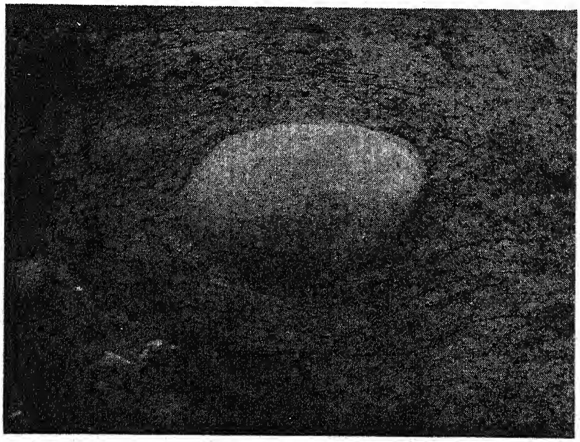


Fig. 219.—Calcareous concretion in Lias shale, Dorset coast, England. Note curvature of beds around the concretion, which is evidence of its contemporaneous origin. Concretion is 15 inches long. (*Photograph by W. A. Tarr.*)

in a rock by ground water long after the deposition of the rock, but there is another group of concretions that are formed at the same time (contemporaneously) as the rocks enclosing them. These concretions con-

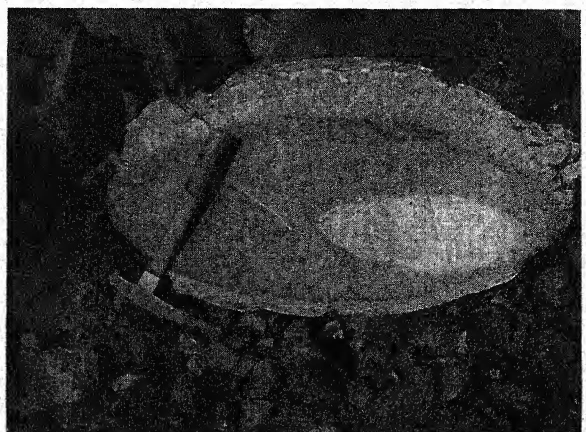


Fig. 220.—Lenticular calcareous concretion from Lias shale, Dorset coast, England. Note layer of cone-in-cone on exterior of concretion.

sist of many different materials but most commonly of calcium carbonate, silica, or pyrite. The concretions may be round, elliptical (Fig. 219), oval, lenticular, nodular, or irregular; in fact their shape may be similar

to that of the subsequent concretions (see Fig. 131, page 129). In size they range from tiny concretions smaller than peas to lenticular masses several feet (Fig. 220) in length and as much as three feet in thickness.

Contemporaneous calcareous concretions are common in shales and clays. These concretions are chemical precipitates, like many limestones. The calcium carbonate is precipitated directly on the sea floor, the growth of the concretion starting about a central point and more material being added on the outside. ([illegible] colloidal silica)

The chert and flint nodules occurring in limestone, chalk, and dolomite are contemporaneous concretions. Their origin has been discussed and illustrations of them given on page 186.

Pyrite occurs as concretions in all kinds of sediments but is especially abundant in shales, carbonate rocks, and coal. The surface of a pyrite concretion may be covered with crystal faces of the mineral.

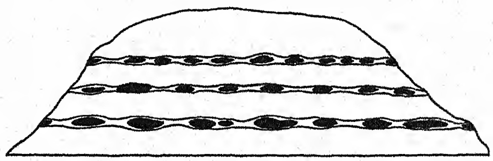


FIG. 221.—Sketch showing the normal arrangement of contemporaneous concretions along a bed.

Contemporaneous concretions occur dominantly along or within a given bed (Fig. 221). Their persistence in this respect makes them of value as criteria in the determination of a bed, even though they may be miles apart. Such a widespread distribution in itself indicates that the concretions were deposited at the same time as the beds.

Stylolites.—Stylolites are very common and interesting features of sedimentary rocks, usually of limestone and dolomite and rarely of sandstone and quartzite. They have already been considered (page 138) under the discussion of the work of ground water, the agent to which they owe their formation.

Cone-in-cone.—Cone-in-cone is another interesting feature of sedimentary rocks that is due to the work of ground water and so has already been discussed (page 138). Cone-in-cone is formed in a fibrous variety of calcite occurring in sedimentary rocks.

Color of Sedimentary Rocks.—The color of a sedimentary rock is due to the inherent color of the minerals composing it or to an extraneous coloring matter introduced at the time of the deposition of the rock or later. The vast majority of sediments possess one of three dominant colors, or mixtures of them in which the shade of color depends upon the proportions of the different colors. These three colors are white, black, and red. Mixtures of black and white materials produce a gray rock, small amounts of black material producing a light-gray (the characteristic

color of most limestones) and large amounts a dark-gray rock. White materials mixed with red produce pink rocks.

The black coloring agent in sedimentary rocks is the carbonaceous material remaining after the decay of organic matter. On weathering, however, a gray limestone invariably becomes buff, yellow, or red. This is because iron minerals had been included with the calcareous materials when the limestone was deposited. In the presence of carbonaceous material, however, iron exists as white or colorless ferrous compounds. When, during the weathering of limestone, however, ground water containing much oxygen enters the rock, the carbonaceous material is oxidized to carbon dioxide (CO_2), which escapes, whereupon the ferrous compound is oxidized to hematite (Fe_2O_3), which is red. The color of hematite is so dominant that a very small amount of it will color the rock a faint shade of red. By uniting with water some of the hematite will form the iron oxide limonite ($2Fe_2O_3.3H_2O$) which produces the yellow and brown colors of the weathered rocks. Mixtures of hematite and limonite produce orange and purple colors. These two iron oxides are very common coloring agents of sediments. The great series of red beds of western United States and of the other countries owe their color to that of hematite. Orange and green colors are produced in sedimentary rocks by various means, some of which are not fully understood.

WEATHERING OF SEDIMENTARY ROCKS

The same agents of weathering, mechanical and chemical, that attacked the igneous rocks act upon the sedimentary rocks, but with somewhat different results, as we shall see, because the sediments themselves are composed of the products of weathering.

Conglomerates, as the name indicates, may be composed of any kind of rock or mineral. As a result each boulder or pebble will weather into the materials which the rock or mineral which it represents would weather into. A conglomerate composed of boulders, cobbles, and pebbles of granite would weather into the same products as a granite, but one composed of particles of different types of igneous rocks, or the different kinds of sedimentary rocks, would weather into all the different products that the weathering of the different rocks present would produce.

Sandstones, however, are composed dominantly of quartz grains, themselves a product that was unaffected by weathering; hence disintegration (by the removal of the cement if any is present) is the chief change, the sandstone becoming a sand again.

Shales are composed predominantly of insoluble clay minerals produced by the weathering of certain igneous rocks. Hence when the shale itself is weathered it becomes again a loose aggregate of clay minerals. Any chemical change is minor in amount. The soil over a shale

is a clay soil which grades directly and almost imperceptibly into the shale.

Limestones, *chalk*, and *dolomites*, being soluble in ordinary ground water, pass back into solution during weathering. Such results of weathering are evident in exposures of limestone, the surface being roughened, pitted, and channeled (Fig. 144 page 137). Some channels are many feet deep and not uncommonly are connected downward with an underground passage or even a cavern. As the limestone or other carbonate rock passes into solution, any insoluble impurities, such as chert, flint, clay, iron oxides, or quartz grains, are left behind and form the mantle rock and soil. This material is usually very red (especially over dolomites), because even the very small amount of iron present in a fairly pure limestone is converted into hematite during weathering and being greatly concentrated in the mantle rock and soil colors them red. Such residual deposits have thus been called *terra rossa* (red earth). Over some dolomites they may contain as much as 10 or 15 per cent of hematite. Terra rossa may accumulate until it is many feet in thickness. The soil, of course, is not so red as the mantle rock on account of the organic matter it will naturally contain. Some limestone soils are even black due to an abundance of organic matter.

The *chert* and *flint* associated with the carbonate rocks are insoluble and so are concentrated in the mantle rock and soil during weathering. In some areas of carbonate rocks containing much chert (some limestones contain 50 per cent of chert), the chert accumulates on the surface (especially the slopes of the hills, from which the fine residual soil is easily washed away) until it completely covers it. Such chert-strewn hillsides look from a distance as though they were snow-mantled. They are waste land. Some of the chert will find its way into the streams and become disintegrated into gravel suitable for use on roads.

Such soluble rocks as *salt and gypsum* readily pass back into solution during weathering, leaving behind any impurities they contain to help in the formation of soil.

Some sedimentary rocks containing *iron minerals* in amounts insufficient to pay to mine the iron may undergo enrichment as a result of the weathering of the rocks. The insoluble iron oxides are left behind and the more soluble materials associated with them are removed. This type of enrichment has changed the original iron-bearing sediments of the Lake Superior region into the high-grade ores found there. Lateritic deposits formed at the surface may be rich enough in iron to mine. These deposits (see page 73) represent one of the end products of weathering.

In the weathering of sedimentary rocks, as in the weathering of igneous rocks, the formation of a productive soil is of the first importance to man. The famous blue-grass region of Kentucky owes its productiveness to its limestone soil. A soil well suited for agricultural purposes

is the sandy loam produced by the weathering of a combination of sandstones and shales.

SUMMARY

The products of the weathering of the primary igneous rocks (as well as some secondary rocks) are transported to the ocean, sorted, and deposited, resulting in a series of sedimentary rocks. Some of these rocks consist of fragments of various sizes, and others are of chemical or organic origin. These sedimentary rocks possess various features which are distinctive of them as deposits made in water.

CHAPTER X

METAMORPHIC ROCKS

As we continue to study the rocks of the earth's surface, we encounter rocks having both structural features and minerals that are different from those of the igneous and sedimentary rocks. A careful study of

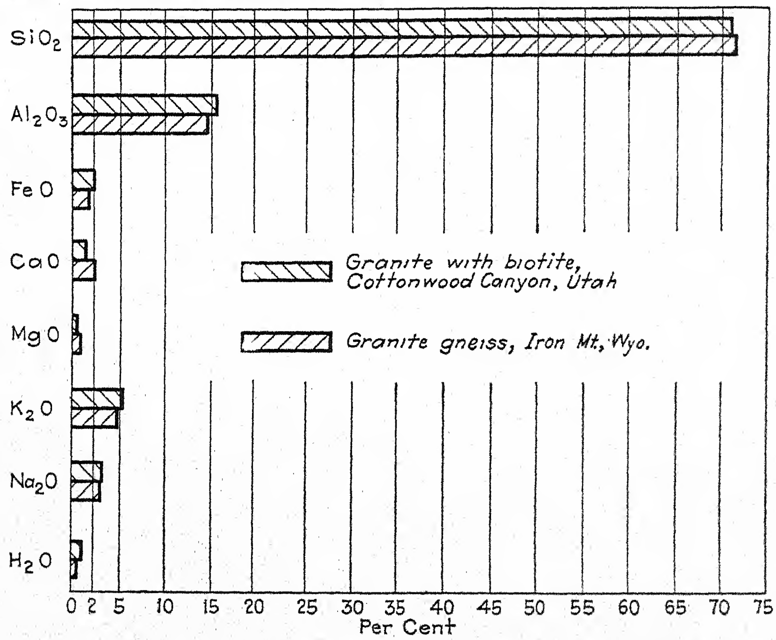


FIG. 222.—Diagram showing similarities in composition of granite and gneiss.

these new rocks, however, shows that, in addition to the different minerals, they contain many that are the same as those of the earlier rocks. This fact and other evidence indicate that these rocks resulted from the alteration of the igneous and sedimentary rocks, and hence they are called *metamorphic rocks*. ("Metamorphic" means "changed in form.") Two important lines of evidence led to this conclusion as to the origin of these rocks. One was that the minerals and structural details of the altered rocks could, in some mountainous areas, be traced into less altered phases that still showed features of the original rocks. The other line of evidence was the discovery, made through chemical analyses, that although the altered rocks looked vastly different, actually they had the same chemical composition as certain sedimentary or igneous rocks

from which, for other reasons, it was thought they might have been derived (Figs. 222 and 223).

There are two types of *metamorphism: regional* and *contact*. Regional metamorphism consists of slow changes due to the normal pressure, heat, and solutions that exist everywhere within the earth's crust, and of

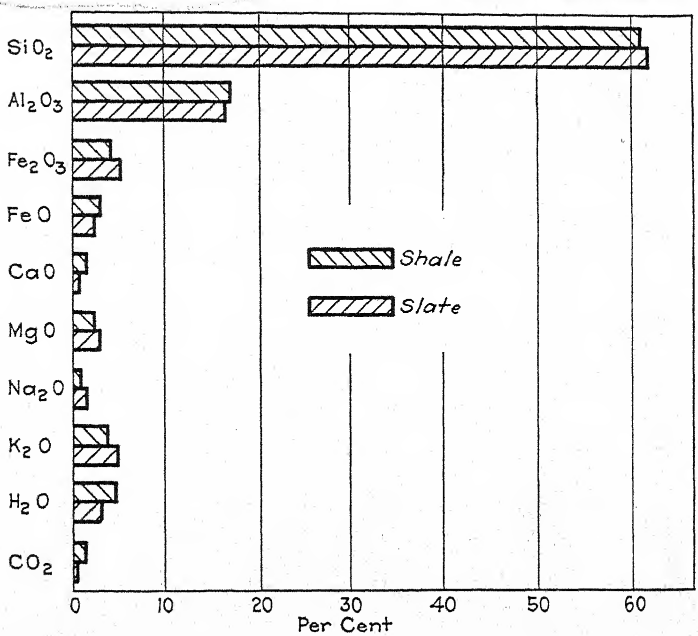


FIG. 223.—Diagram illustrating the similarity in composition of shale and slate.

other changes, probably more rapid, that are caused by the folding and crumpling (Fig. 224-A) of strata during mountain making. Contact metamorphism is due to the exceptionally high temperature, pressure, and very strong solutions that are connected with the injection of lava into a rock (Fig. 224-B). The alterations produced during contact meta-

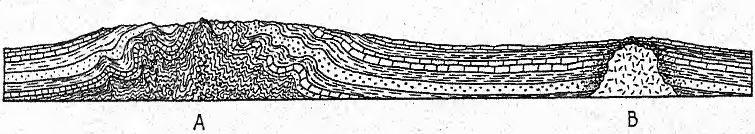


FIG. 224.—(*A*) Folding and crumpling such as produces regional metamorphism; (*B*) contact metamorphism around an igneous intrusion.

morphism are very marked adjacent to the intrusion but die out, as a rule, in half a mile. Most metamorphic rocks have been formed by regional metamorphism; hence our discussion will be concerned mainly with that type of change. Contact metamorphism is of economic importance, however, as it produces some of our valuable metal-bearing deposits.

Where Metamorphism Occurred.—Numerous attempts have been made by geologists to divide the crust of the earth into zones in which certain changes in the rocks occur (Fig. 225); for example, the outer zone of weathering and below it the zone of cementation. Needless to say, such zones have arbitrary limits; the zone of weathering, for example, ranges from a few inches to hundreds of feet in thickness. In the discussion that follows we shall refer to the *zone of metamorphism* but it should be understood that it begins at the various depths below the surface at which metamorphism begins.

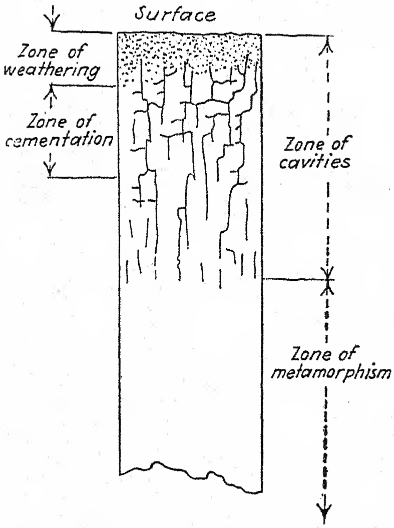


FIG. 225.—Diagram showing zone in outer part of the earth.

The occurrence of metamorphic rocks in the central part of mountain ranges, in which extensive erosion has exposed them, and the additional fact that the surface or near-surface sedimentary and igneous rocks are the fresh unaltered material, indicate that metamorphism usually occurred at a considerable distance below the surface. That this distance is not necessarily great has been proved in many mountainous areas, such as the Appalachian region where the depth was measured and found to be within a few thousand feet of the surface. We can thus deduce something about the pressure and heat that caused the formation of metamorphic rocks.

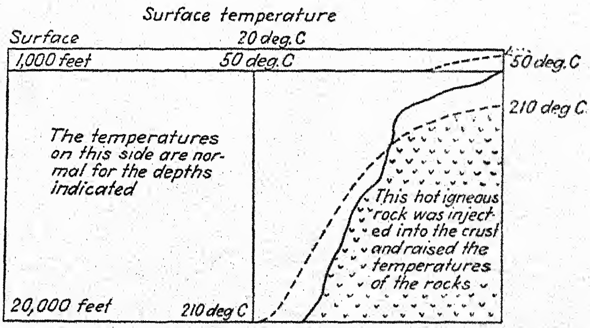


FIG. 226.—Diagram showing increase in temperature due to an igneous intrusion.

Heat in the Metamorphic Zone.—A physical factor of great importance in the metamorphic zone is heat. Tests made to determine the temperature in deep wells in many parts of the world prove that there is a slow increase in temperature downward. The rate is different in different

areas; where there has been recent igneous activity the temperatures are high near the surface (Fig. 226); in others they are low. At depths of 20,000 feet the temperatures, if uninfluenced by igneous rocks, are probably much the same. In a deep well in Pennsylvania the temperature of the rocks just below the surface was 10°C. and at the bottom of the well, at a depth of 7,756 feet, it was 77°C. The temperature was 77°C. at 8,300 feet in a well in the Big Lake oil field in Reagan County, Texas. In some deep (6,000 to 7,000 feet) mines, temperatures are 44 to 49°C., and special means of ventilation to cool the mines must be employed.

The rate of temperature increase downward has been assumed to be 1°C. for 100 feet; at that rate the boiling point of water should be reached at about 8,500 feet. In the two wells mentioned above, however, the temperature at such a depth was much below the boiling point of water; in fact several wells have been drilled to depths of 10,000 feet or more in which the boiling point of water was not reached. It must be inferred, therefore, that the rate of 1°C. for 100 feet represents too high a temperature increase downward, though the rate is probably affected by many factors that we are unable to evaluate or possibly of whose existence we have no knowledge. The important fact is, however, that any rock occurring at depths of a mile or more exists under conditions of considerable heat. The temperature deep within the earth is probably thousands of degrees; but, as the great pressures there prevent expansion, the rocks cannot become liquid except locally.

THE AGENTS OF METAMORPHISM

The alterations that occur in rocks and minerals are both chemical and physical. The *chemical agents* of metamorphism, *water* and *gases*, change the existing rocks and minerals into new ones; and *pressure*, the *physical agent* of metamorphism, brings about flattening, elongation, and a flowing of the rock constitutents. It will be seen in our discussion of metamorphism that most of the alterations are produced partly by chemical and partly by physical means and, moreover, that the chemical and physical agents may both be operative at the same time in producing such alterations. So it will not be possible wholly to separate the discussions of chemical and physical metamorphism.

Chemical Agents

The chemical changes are caused largely by water, though it is aided by the various acids and gases it contains and by heat. Under special conditions, such as the injection of lava into a rock, the metamorphism may be very intense due to the high temperatures in connection with the strong acids and gases that may be present. Deep within the crust the heat might be so great that all of the solutions would be converted into gases, and if so, the metamorphic effects would be intensified. At

these great depths, pressure, the physical agent of metamorphism, would aid the chemical agents in their work by crushing the rocks into smaller grains that would be more easily attacked.

Water and Gases.—Water is so effective an agent of metamorphism that even cold water can bring about changes (as we have seen under Weathering). However, as hot water has a much greater efficiency, deep-seated metamorphism is the most marked. When the temperature is high enough, the water is converted into steam, which, nevertheless, is able to carry on the chemical changes just as the water is. Such gases as oxygen, carbon dioxide, sulfur dioxide, chlorine, or fluorine greatly increase the ability of the water to accomplish chemical changes. The changes take place slowly, of course; but, as the time element in geologic processes is ample, great changes are finally accomplished.

The water in the rocks may have been included in them originally, as water in shales or sandstones; it may be contained in hydrous minerals, such as the clay minerals; or it may have worked its way into the rocks from below. When a shale or other water-bearing sedimentary rock becomes deeply buried, the heat causes the liberation of water from the hydrous minerals. This process, while altering the hydrous minerals, liberates some of their water, which aids in bringing about the chemical changes. In the deeper zones carbon dioxide would be liberated, and during the breaking up of pyrite by solutions sulfur dioxide might be released. Through all these means, water and gases may be made available for chemical work.

Chemical (Mineral) Changes

The chemical changes through which new minerals are produced are the most important changes in the formation of metamorphic rocks. These changes are going on constantly, though usually slowly. The number of new minerals that are formed is large and a full discussion of their formation would be out of place here. We can follow the process of a few of the simpler changes, however, and thus have some idea as to how the metamorphic agents accomplish their work. The rule is that *if a new mineral forms it must be stable under the new physical conditions.* Thus the clay minerals formed at the surface of the earth are unstable far below and so are altered to minerals that are stable there. This law of the alteration of minerals should be kept in mind throughout our discussion of metamorphism.

The Change of Limestone to Marble.—Probably the simplest chemical change is that of a limestone or dolomite to marble, as this alteration involves the formation of no new minerals. Marble is coarser grained than limestone and so the change has been simply one of small grains into large ones. The original calcite grains in the limestone differed in size, and so the smaller grains went into solution faster than the large ones

and the material was deposited on the larger grains. Thus it is another example of large grains' growing at the expense of smaller ones, such as we have seen in discussing the formation of the sedimentary rocks. As the alteration of the limestone proceeds the fine-grained limestone becomes the coarser-grained marble (Fig. 227). This change, which is a common one in metamorphism, is known as *recrystallization.*

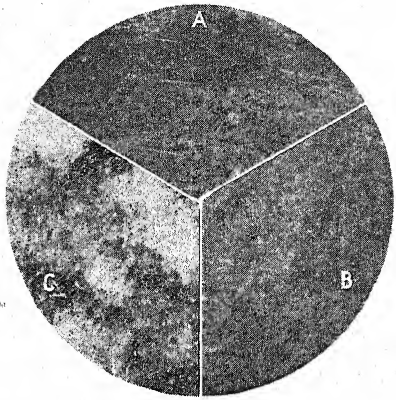


FIG. 227.—Dense limestone (*A*) altered to fine-grained limestone (*B*) and then to marble (*C*)—all changes due to recrystallization.

The Change of Sandstone to Quartzite.—The *cementation* of the grains of a sandstone by quartz is a simple sedimentary process that is included by some authors under metamorphism. It does not belong here, however, as it merely involves the carrying of silica in solution and its deposition as quartz upon the grains of sand (also quartz) until the openings in the sandstone are filled (Fig. 228). This process is mere cementation, which may occur from the surface of the earth downward. Sandstones and quartzites do undergo metamorphism, however, but their alteration, being due to pressure, will be noted under the discussion of physical changes.

The Change of Shale to Slate and Schist.—The alteration of shale to slate and schist is a much more complex process, as it involves several changes. Shale consists predominantly of clay minerals, colloidal silica, potash, and water. Some shales contain quartz, mica, and iron oxides, also. After a shale is buried and subjected to increasing heat, the first change is a loss of water. This water was contained largely in the colloidal silica ($H_2O.SiO_2$) of the shale, and after its elimination the SiO_2 (which is quartz) binds the clay particles together into a hard rock. This simple alteration, called *dehydration,* alone, hardens the shale, and if no other change occurred a hard flint-like rock called *hornstone* or *baked shale* (Fig. 229) would result.

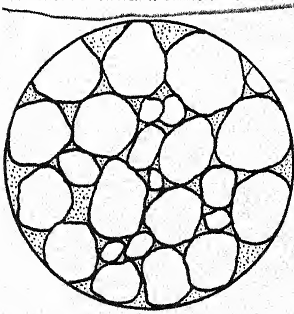


FIG. 228.—Diagram showing grains (white) of a sandstone cemented with quartz (stippled) to form quartzite.

During metamorphism part of the water of the clay minerals is driven off by heat and so is able to aid in the chemical changes. The potash of the shale unites with the remainder of the water, the alumina, and the silica of the clay minerals to form little scales of *muscovite mica,*

which is the dominant constituent of most *slates*. Some shales do not contain enough potash, however, to form mica from the clay minerals, whereupon their alumina and silica unite, forming large dark crystals which give the rock a spotted appearance. One variety (staurolite) of these crystals occurs as crosses, which in Virginia and other places are collected and sold as "fairy crosses" (Fig. 230). Should pyrite have

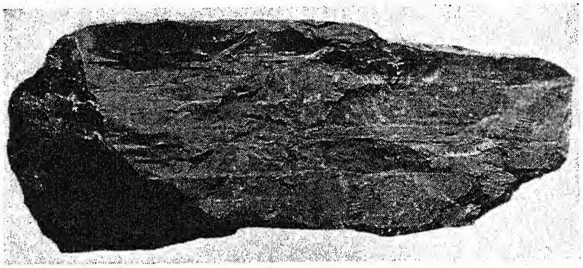


FIG. 229.—Hornstone or baked shale from Breckenridge, Colorado.

been present in the original shale, it might be recrystallized during the metamorphism into larger pyrite crystals (Fig. 231). Black slates are due to the formation of *graphite* scales from carbonaceous material in the original shale. If the original shale was yellow, it contained limonite, which during metamorphism would lose its water and become hematite, and thus a red slate would be formed. This is not all of the

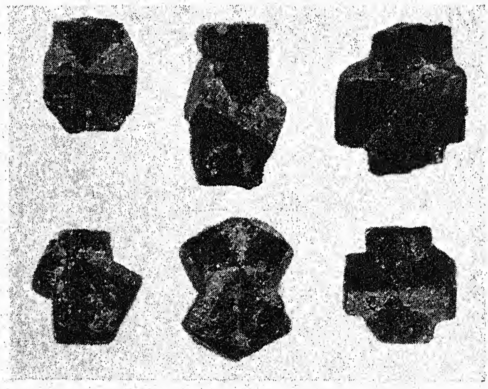


FIG. 230.—Staurolite crystals. One-half natural size.

story, however, for pressure (as we shall see in studying physical metamorphism) causes the flakes of mica to assume a parallel arrangement which gives to slates their property of splitting into sheets.

If a slate is subjected to further metamorphic action by hot solutions, the larger scales of mica will grow at the expense of the small ones and a mica *schist* will result.

The Change of Granite to Gneiss.—The alteration of a granite, or any other igneous rock, to a metamorphic rock is by far the most complex metamorphic process. The quartz is not altered, as a rule, but it may be badly crushed. The feldspar may undergo marked

K, Na, Ca, al, SiO_2

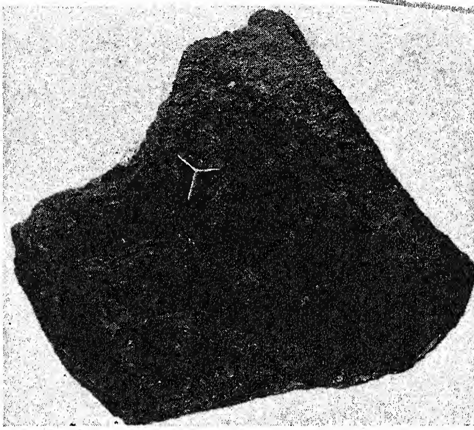


FIG. 231.—Pyrite cube embedded in a black slate. One-half natural size.

changes, however, the most common of which is the alteration into muscovite mica. If the igneous rock contains mafic minerals, such as hornblende or pyroxene, they are altered to hornblende needles (pyroxene becomes hornblende), chlorite, biotite mica, or *garnets* (Fig. 232). A gneiss (originally a granite) containing garnets six inches to a foot or more in diameter occurs in the Adirondacks. Garnets are very common in all kinds of metamorphic rocks, and some of them are used as gems (Fig. 233).

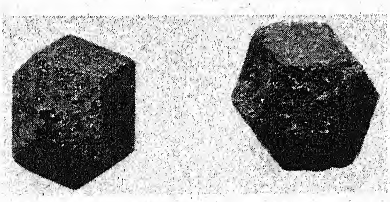


FIG. 232.—Garnets (12-sided form). One-half natural size.

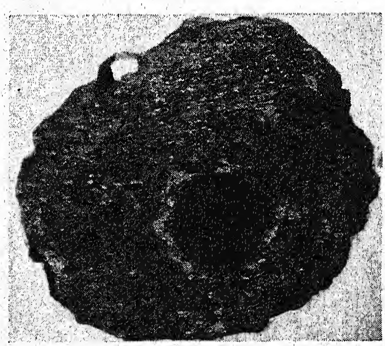


FIG. 233.—Garnets in schist from Wrangell, Alaska. One-fourth natural size.

Summary.—Solutions, aided by heat, take material from one mineral and add it to another to form a new mineral, thereby producing a new type of rock (metamorphic rock). Many different minerals are formed, but the most common ones are the micas, hornblende, chlorite, garnets,

and quartz. In the formation of some metamorphic rocks material is added from another rock nearby; in the formation of others no material is added or removed, one mineral merely changing into another or one mineral grain merely growing larger at the expense of a smaller grain of the same mineral.

The Physical Agent (PRESSURE)

Pressure operates everywhere in the earth's crust, but is, of course, more effective at the greater depths. In the outer 40 to 50 miles the pressure may cause movement (flowage) in the solid rocks. Such movement is an important factor in the formation of the banded rocks.

Pressure.—We know that pressure increases downward due to the weight of the column of rock above any given point. This pressure can

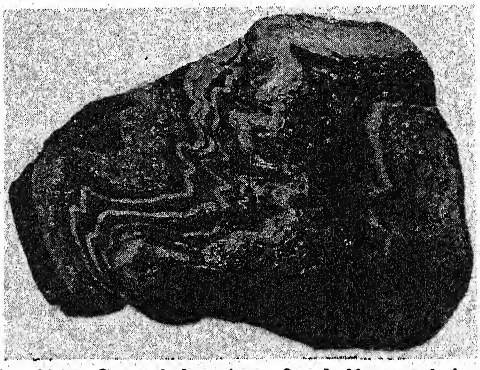


FIG. 234.—Crumpled gneiss. One-half natural size.

easily be computed as follows. The average specific gravity of the outer part of the earth is commonly considered as 2.7. Using this figure and the weight of a cubic foot of water (62.5 pounds), the weight of a cubic foot of average rock is found to be 168 pounds and the weight of a column of rock 1 foot high and 1 inch square 1.16 pounds. The pressure on 1 square inch at a depth of 1,000 feet would thus be 1,160 pounds; at one mile about 6,000 pounds; and at 10 miles 60,000 pounds or 30 tons. (The pressure at the center of the earth is estimated to be 45,000,000 pounds per square inch.) These great pressures would aid in producing profound changes in a rock. Experimental studies have shown that at a depth of approximately 11 miles the strongest granite known would probably flow like asphalt. Below this depth an opening could not exist in the earth's crust. Rocks weaker than granite would flow at depths much nearer the surface; in fact shales would flow within 1.5 miles of the surface. This actually occurred in a deep well in Pennsylvania, the shale flowing and crushing the iron casing in the well as though it had been a paper tube.

If the pressure in the metamorphic zone is sufficient to crush the rocks, they should show evidence, such as folding and crumpling, of having flowed or moved. This evidence of flowage (Fig. 234) is present in many metamorphic rocks. Dikes and sills (the tabular masses of igneous rocks that are intrusive in other rocks) are normally straight (see Fig. 19, page 20) but in metamorphic areas they are much folded and crumpled (Fig. 235).

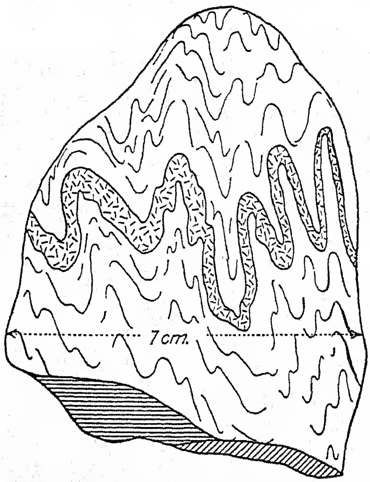


FIG. 235.—Sketch of a dike 18.5 centimeters long crumpled into a space of 7 centimeters.

The pressures within the earth's crust (Fig. 236) are *uniform*, or *directional*, which is of course nonuniform. Uniform pressure is effective in reducing the volume of a substance, and nonuniform or directed pressure leads to movement and changes the shape of minerals, as we shall now see.

Physical (Structural) Changes

A striking characteristic of most metamorphic rocks is that they are *banded* or *foliated* (having curved bands) and have the property of cleaving more or less readily along these bands or planes. This banding and cleavage are due to the movement (shearing) that is induced by the physical agent pressure.

The banded character of metamorphic rocks is utilized in naming the two most common types, gneiss and schist. If the bands in the rock are fairly coarse ($\frac{1}{8}$ to $\frac{1}{4}$ inch in thickness), the rock is a *gneiss* (Fig. 237);

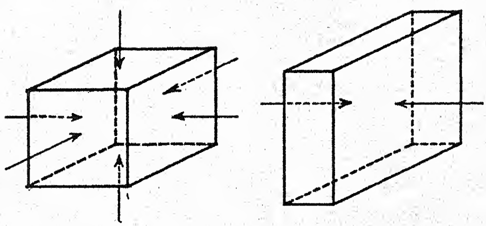


FIG. 236.—Diagram at left illustrates uniform pressure; diagram at right, directional pressure.

if the bands are thin and the rock cleaves readily, it is a *schist* (Fig. 238). A slate (Fig. 239) has this cleavage property very highly developed and may thus be split into remarkably thin sheets.

Banding the Result of Directional Pressure.—Directional pressure involves movement and shearing and is the dominant factor in forming the banded, cleavable rocks. The new minerals that develop during

chemical metamorphism are, as a result of directed pressure, dominantly flat, tabular, or elongated blade-like forms. The common minerals that have these shapes are *muscovite, biotite, chlorite, talc* (a hydrous magnesium silicate), and a bladed variety of *hornblende*. These minerals develop with their flat sides at right angles to the direction of the pressure; thus, as was noted in discussing the formation of slate, the directional pressure caused the mica to become parallel, giving the slate its cleavage. Cleavage planes developed by metamorphism in a folded sedimentary rock are generally independent of the bedding planes and are always at right angles to the direction of the pressure (Fig. 240).

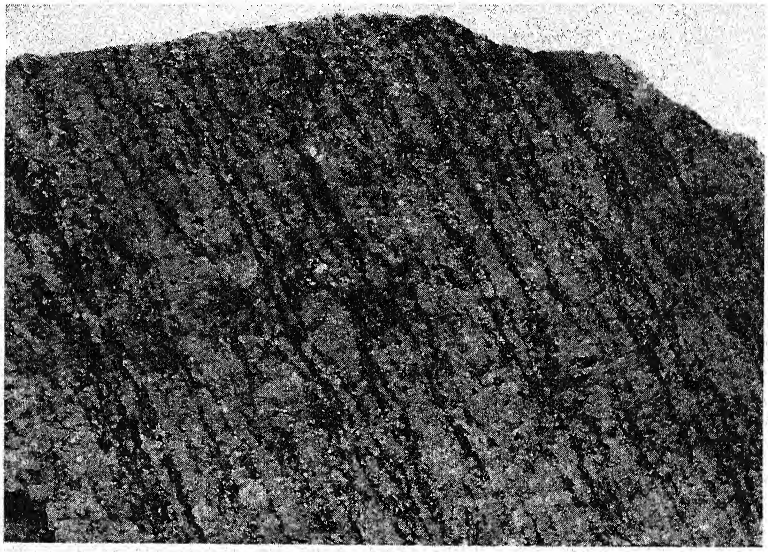


FIG. 237.—Gneiss. Note elongated feldspar crystals. One-half natural size.

In those minerals which do not undergo chemical changes the grains are either crushed and elongated (Figs. 237 and 241) by the pressure and movement or are compelled to rotate or flow until they are parallel to each other and at right angles to the pressure. It is thus that gneiss, consisting as it does chiefly of crushed and elongated quartz and feldspar grains, possesses a coarser banding than a rock that is composed of tabular metamorphic minerals. Pure sandstones and quartzites are crushed as a result of directional pressure, and although the banding developed is poor they are known as *quartz schists*. If the sandstones and quartzites were clayey, considerable mica might form and so a good schist would be developed.

The mottled varieties of marble are the result of directional pressure and the accompanying movement. This movement was made possible by the fact that calcite and dolomite have perfect cleavage in three

directions. As a result of the flowage or movement the rock is twisted and crumpled until all evidence of the bedding planes of the limestone from which the marble originated is lost.

FIG. 238.—Schist. Note thin banding and garnet crystals. One-half natural size.

In the restricted space in which metamorphism occurs it is inevitable that there should be crowding and jamming of rock masses. This results in the folding and crumpling that is characteristic of the metamorphic rocks (Figs. 234 and 242). Thus directional pressure and its accompanying movement not only cause the parallel banding characteristic of metamorphic rocks, but also the folding and crumpling seen in all kinds of metamorphic rocks. As directional pressures operate chiefly nearer the surface where upward movement is possible, folded and banded metamorphic rocks are most abundant in the crust. They are especially abundant, of course, in the intensely folded strata of mountainous regions.

Massiveness the Result of Uniform Pressure.—When a new mineral formed by chemical metamorphism is subjected only to uniform pressure during its formation, the mineral crystal will be nearly equidimensional,

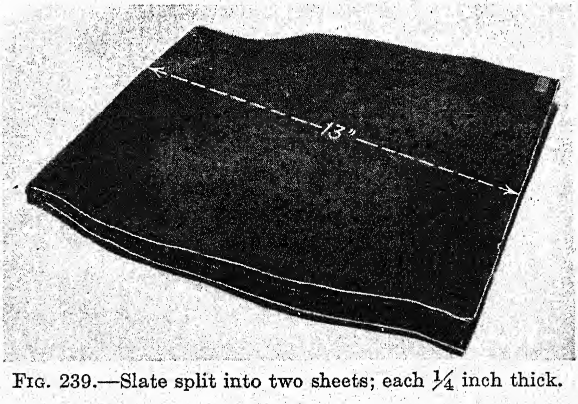


FIG. 239.—Slate split into two sheets; each ¼ inch thick.

such as cubes of pyrite (Fig. 231), twelve-sided garnets (Figs. 232 and 233), or the staurolite crystals (Fig. 230). All these minerals are very dense and heavy as their molecules have been forced close together by the uniform pressure which, therefore, accomplishes volume reduction.

These minerals are common in schists and gneisses where they develop after the formation of the banding that was caused by directional pressure. The growth of these later minerals under the conditions of uniform pressure is due to a continuation of the chemical changes, the new minerals forming out of the materials around them.

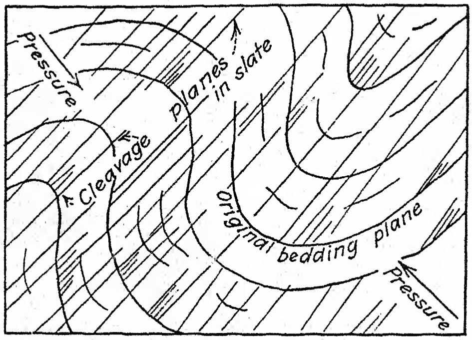


Fig. 240.—Sketch of section of slate quarry, showing how cleavage planes of the slate are at right angles to the pressure and independent of the bedding planes.

Massive Metamorphic Rocks.—Two common massive metamorphic rocks are *marble* and *serpentine.* The massiveness of marble is due to the fact that its formation (which we learned was a recrystallization of limestone) was accomplished under conditions of uniform pressure. Serpentine (a hydrous magnesium silicate) also formed under uniform pressure, but by the alteration of minerals (as olivine) rich in magnesium. Serpentine is a green mottled rock (Fig. 243). Both marble and serpentine are widely used for building purposes. Another massive metamorphic rock developed under uniform pressure is *greenstone.* It is formed when the dark mafic minerals in a gabbro or basalt alter to chlorite, which gives the rock its green color. It may be noted that if a greenstone later became involved in directional pressure it might be converted into a chlorite schist.

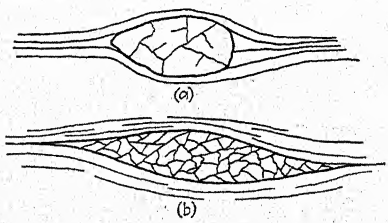


Fig. 241.—Sketch of pebble of quartz (*a*) before and (*b*) after crushing and elongation.

CLASSIFICATION OF METAMORPHIC ROCKS

In the previous chapters on igneous and sedimentary rocks, tables of the names of the more common rock types were developed. Tables of value may now be constructed which will include these earlier rocks with their metamorphic derivatives. It must be remembered, however, that there are hundreds of varieties of gneisses just as there are hundreds of kinds of granites and that there are many kinds of schists, slates, and marbles. Therefore many names are applied to a given metamorphic

rock; for example, there are biotite gneisses, hornblende gneisses, garnet gneisses, and garnet-biotite gneisses. Muscovite and biotite schists are especially common and are usually called "mica schists." There are also garnet schists and garnet-muscovite schists.

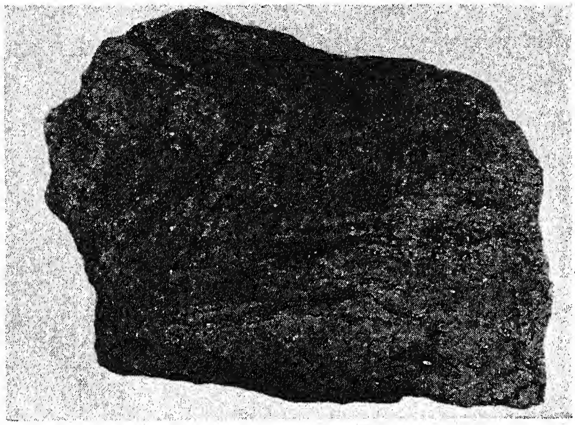


FIG. 242.—Gneiss. One-fourth natural size.

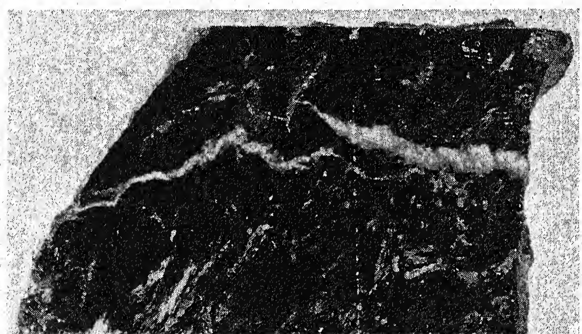


FIG. 243.—Serpentine. One-fourth natural size.

The following table shows the dominant types of metamorphic rocks that are derived from the igneous rocks.

METAMORPHIC ROCKS DERIVED FROM IGNEOUS ROCKS

Igneous Rocks	Metamorphic Rocks
Granite, diorite	Gneiss, schist
Gabbro	Hornblende gneiss, hornblende-chlorite schist
Peridotite[1]	Talc schist, chlorite schist, serpentine
Felsite, felsite porphyry	Mica schist
Basalt, basalt porphyry	Chlorite schist, hornblende schist, talc schist, greenstone
Volcanic glass, tuff	Mica schist

[1] An igneous rock composed dominantly of olivine. Introduced here because of the economic value of some of its metamorphic products.

Some of the metamorphic rocks formed from the sedimentary rocks are shown in the table following.

METAMORPHIC ROCKS DERIVED FROM SEDIMENTARY ROCKS

Sedimentary Rocks	Metamorphic Rocks
Conglomerate	Gneiss
Sandstone	Quartz-hornfels, quartz schist
Siltstone and shale	Slate, mica schist
Limestone and dolomite	Marble
Iron ores (limonite and hematite)	Specularite schist, magnetite[1] schist, magnetite ore
Coal	Graphite

[1] Magnetite is a black magnetic iron oxide.

SUMMARY

Metamorphism is the alteration of some previously existing rock by pressure, heat, and water, usually under the conditions that exist at considerable depths. The metamorphic agents are always in operation beneath the surface, converting every mineral into another of a type that can exist under the pressure conditions at that place. The new minerals are generally more complex in composition than the original minerals. The combined results of the metamorphic processes are the metamorphic rocks with their many new minerals and structures. They form a group of rocks that is very abundant in many parts of the earth's crust.

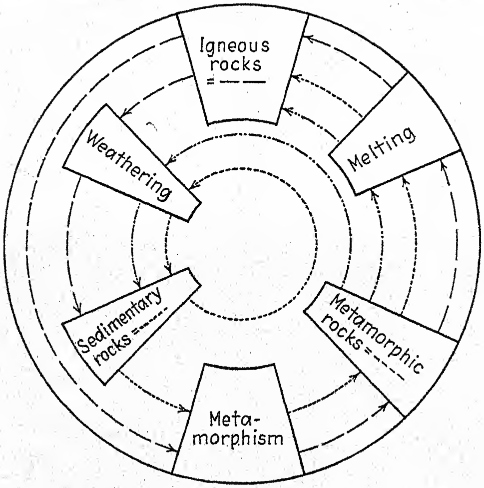


FIG. 244.—Diagram representing the rock cycle.

The end of metamorphism would be attained when the temperature became high enough (between 600 and 900°C.) to melt the metamorphic rocks, whereupon they would become a liquid magma or lava, which upon cooling would become some type of igneous rock again. This would complete the cycle of igneous rock to sedimentary rock to metamorphic rock and back to igneous rock again, as is shown in Fig. 244. This sequence of events has undoubtedly taken place many times.

CHAPTER XI

SNOW AND ICE AND THEIR GEOLOGIC WORK

The geological changes wrought by snow and its products are distinctive not only in the details of their results but also in their distribution over the earth as a whole. Other agents, such as streams and wind, operate in every climate and altitude, but snow is unknown or fairly unique to people of vast areas.

In regions where snowfall is common most of the work accomplished by it results from snow melt and the water thus formed, an indirect work so far as the snow is concerned. In mountain areas a destructive work, performed by snow, as such, appears in many places, the results of snowslides.

Snowslides.—On steep mountain slopes snow may accumulate to such depths that its weight is too great for its grasp on the surface. The drift starts moving with an almost imperceptible creep, speeds up, and gaining momentum, plunges down the slope, twisting and breaking even the largest trees and carrying with it great quantities of loose rock. Many an Alpine village has been destroyed by such an avalanche. Similar slides are not uncommon in the western mountains of North America and in all high mountains.

The slide remains as a rock-filled snow bank until the snow melts and then its effects become evident. A great bare patch on the mountain side almost free from loose rock indicates the path of the slide, and a heterogeneous mass of rock and twisted trees marks the end of the avalanche. The many snowslide scars and accompanying heaps of rock waste in the Rocky Mountains bear mute witness to the local efficacy of snow as a destructive agent. However, the changes accomplished by snowslides are insignificant as compared to those brought about by snow that changes into ice and forms glaciers.

Snow Fields.—In high altitudes and high latitudes are large areas within which snow persists the year round, and although large patches within such areas may be bare during part or all of the year the permanent drifts are known as snow fields. Drifts persist although evaporation and melting may greatly restrict the size of the snow patches. The primary factor that determines the formation of snow fields is the excess of snowfall over waste; it follows that of two areas at the same altitude one may be a snow field and the other, because of the smaller snowfall, may be bare during much of the year.

The snow line is formed by connecting the lowest margins of snow-drifts that persist throughout the year. At the equator in South America the snow line is at an elevation of about 18,000 feet, in Mexico at about 14,000 feet, at the northern boundary of the United States at about 10,000 feet, and at a distance of 15° from the pole it is at sea level in some places.

Since the snowfall exceeds the waste in snow fields it is evident that in such places the snow mantle increases in thickness from year to year. It is also evident that there is some limit beyond which the increase cannot go, as otherwise all the water of the earth would be locked up in snow fields. This limit is determined by the weakness of the ice, which

Fig. 245.—Snow field 20 miles southeast of Juneau, Alaska. (*Official photograph, U. S. Navy Air Corps.*)

lacks the rigidity to hold its shape under the weight of the accumulating snow and spreads out beyond the confines of the snow field into lower altitudes or latitudes where melting checks further advance. As an example consider an area like Greenland and suppose that the snowfall were 10 feet per year and 9 feet were lost by melting and evaporation.[1] In 5,000 years the snow would accumulate to a depth of 5,000 feet, which would be sufficient to cause movement of the snow field. As the temperature would be higher nearer the sea the melting would be greater, and the snow would be thicker on the interior of the island than near the water. The weight of 5,000 feet of snow and ice would be so great as to crush the ice at the bottom and to tend to make it move laterally. The outward movement of the snow becomes a necessity, obeying ordinary physical laws.

[1] At the rate of 1 foot excess snowfall over waste per year all of the water on the earth would be piled up on Greenland in one-fifth the time it would take to base-level the North American continent at the present rate of erosion.

Glaciers.—A mass of snow and ice set in slow motion on land by its own weight is called a glacier. Glaciers will form wherever the yearly snowfall exceeds the yearly waste for long enough time for the snow to become thick enough to start movement in the ice mass. Areas with small snow fields may have no glaciers but the distribution of glaciers is nearly the same as that of snow fields. They are present in high mountains in equatorial regions, toward the poles descend to lower and lower levels, and reach sea level in some places more than 15° from the poles.

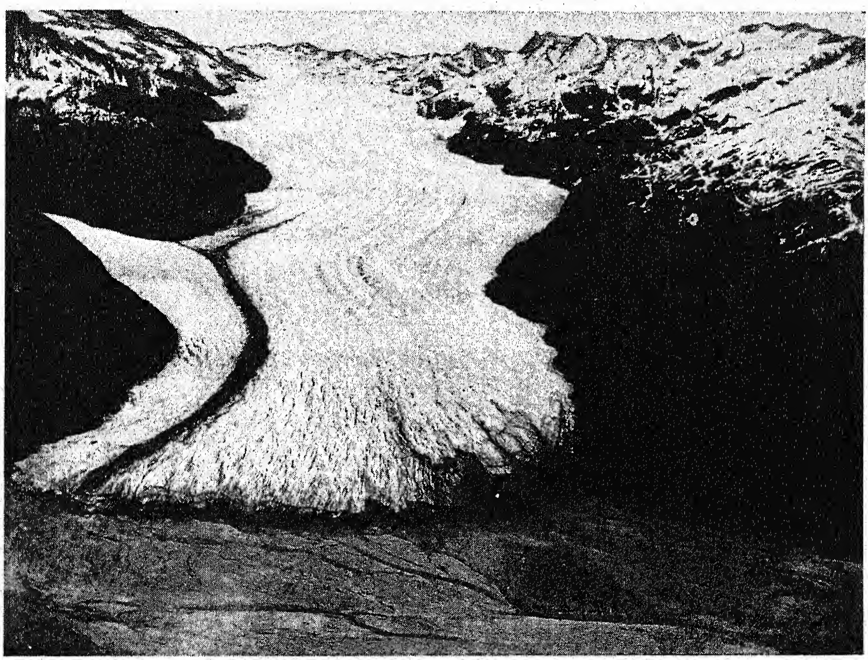


FIG. 246.—Bond Glacier, Thomas Bay, Alaska. (*Official photograph, U. S. Navy Air Corps.*)

In tropical and temperate regions glaciers form only in mountain valleys and for that reason are called *valley glaciers.* In frigid regions land areas at low altitudes may be covered with glaciers. As some such glaciers cover large areas, Greenland being a good example, they are called *continental glaciers.*

Glacial Ice.—Although glaciers form from snow they are made up of solid ice. Throughout the almost infinite variety of shape among snow flakes certain broad characters are constant: all are flat, thin, and lace-like. But the delicate ice crystal changes rapidly once it has reached the earth. Ice evaporates even though the temperature of the air is below freezing, the delicate points of the flakes waste away, and at the same time there is a tendency for recondensation about the central, more solid part of the flake. These two processes, waste of delicate points and growth of center, convert the flakes into tiny spheres. The change of

fluffy to granular snow surface in a few days at the most is common in temperate climates. The process is hastened by rise in temperature and a very short melting period each day quickly converts a considerable depth of flakes into grains with little total loss to the pile through melting. In a snow field there is a steady granulation of the snow throughout the winter and the residue at the end of the summer is completely grained.

This graining is only an incident in the conversion of snow to solid ice. Even slight melting at the surface of the accumulation furnishes water that descends to refreeze in the intervening pores; apparently no considerable thickness of grained snow can exist without being thoroughly cemented in its lowest part. Pressure on the lower part of the granular snow from the overlying snow tends to compact the lower part into ice. The combined granulation, melting, refreezing, and pressure, tend to make the ice of the snow field and glacier nearly as dense as that from the ordinary freezing of water.

Stratification is one of the most striking features of glacial ice, a layered structure that comes largely from its mode of origin. Each year there is added a layer of ice, the remains after the year's melting has taken its toll of the total snowfall. At least a small amount of dust settles with every snow fall. Most of the sediments freed by the year's melting accumulate on the surface to mark the end of the active melting season by an exceptionally dirty band. If the snow has accumulated in a steep-walled mountain valley, much coarse debris may have been released high up by spring thaws to roll to the ice surface in the valley.

Another feature, entirely inconspicuous but possibly of much greater importance than the banded structure, is the intimate structure of the ice, minute spheres which result from snow granulation and later melting and freezing. A piece of clean glacial ice does not show this even under the microscope, but the structure remains throughout the life of the glacier and when the ice partially melts it breaks down into small spheres. It would seem that the cementing ice had slightly different properties than the spherical ice and possibly this accounts in part for the motion peculiar to glaciers. We might liken the mass to grains of sand held together by a somewhat plastic cement.

Glacial ice is hard and in a real sense very rigid. A stone in its midst is as firmly grasped as one frozen into the ice of a pond. The ice snaps and cracks under stresses that tend to deform it just as does ordinary ice. Even so it molds itself into the tortuous curves of valleys very much as though it were a viscous liquid.

GLACIAL MOTION

To say that we understand glacial motion would be misleading, although many peculiarities of the motion are common knowledge.

For instance, warm glaciers (near the melting point), and therefore wet glaciers, move faster than cold dry glaciers. Or again, glaciers may override obstructions, actually move uphill for short distances, provided the glaciers are sufficiently long and thick. Most evident is the fact that glaciers do not slide as a unit down valleys, although minor parts

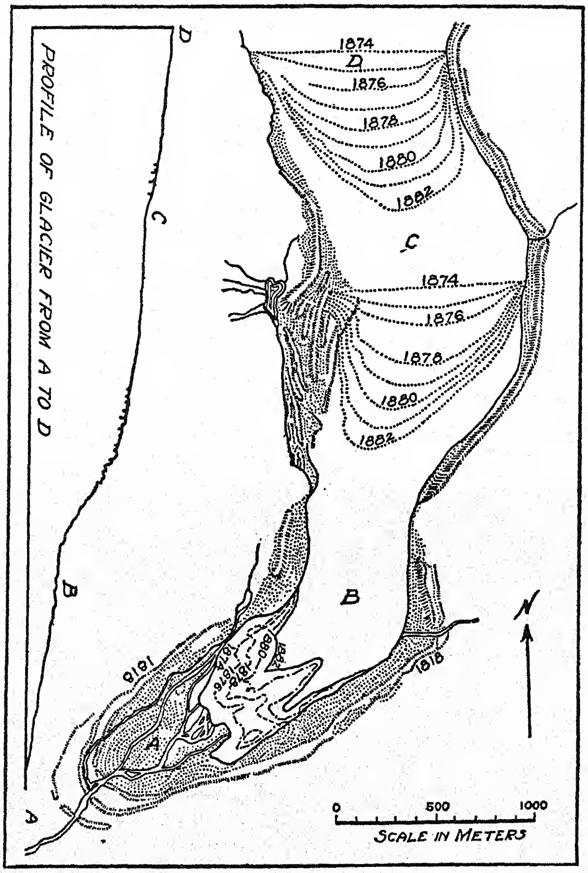


FIG. 247.—Profile of the Rhone Glacier, Switzerland, and sketch showing differential movement of ice. The most rapid movement is near the middle of the glacier. (*From Emmons, Thiel, Stauffer, Allison "Geology," after Heim.*)

of a valley glacier are pushed like a great rasp along the valley bottom and sides.

We can appreciate the distinctive movement of glaciers by visualizing a great ice cap like that of Greenland. Let us assume that at the center there has been built up a thickness of several thousand feet. The ice in the lower part of this pile is under pressure so great that it must be squeezed laterally, a thrust that is transmitted to the margins. The ice at the margin is thin, for the position of the margin as determined by

melting is just compensated for by forward movement of the ice. The great pressures maintained at the center of the cap are lacking at the margin and this part of the ice is not molded but shoved forward—is actually pushed over the underlying surface. Gravity is the indirect cause of the lateral movement of the margin, but freezing of water within the ice is of some importance, and possibly a close second to gravity. All the waters resulting from the melt of surface ice tend to descend through cracks to refreeze at lower levels and in expanding add to the rigid thrust.

Another factor probably of some importance in the movement is the alternate expansion and contraction of the ice with seasonal or more rapid temperature changes. Numerous crevasses permit the descent of comparatively warm air and water and it is likely that the temperature of the ice varies considerably from time to time even at considerable depths. Movement by expansion and contraction seems particularly adapted to valley glaciers in which the weight from thickness is not great. When the ice is exceptionally cooled it contracts, not as a continuous unit but by cross-cracking into many units. Snow, rock débris, and ice formed from surface melt tend to fill the cracks and the linear expansion accompanying a subsequent rise in temperature is possible only as the ice moves downward or outward.

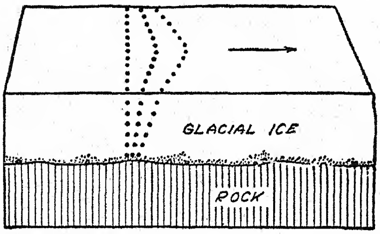


FIG. 248.—Diagram illustrating the differential movement of a valley glacier. Stakes driven in a straight row across the top of a glacier, in a short time show a curve down-valley. Pegs placed on the side of the glacier demonstrate that the top moves faster than the bottom. (*From Emmons, Thiel, Stauffer, Allison "Geology."*)

Rate of Movement.—Judged by most standards all glaciers move slowly, and it has been only in comparatively recent times that movement has been recognized as one of their characteristics.

A young Swiss, Louis Agassiz, was the first to prove definitely the movement of glaciers. While a boy he noticed that the relationship of bodies of ice in some of the valleys of the Alps was not constant with landmarks on the sides. He drove stakes in the valley outside the ice and stakes in line with them on the ice and found that with the lapse of time the relationship of the stakes changed; those on the ice moved down-valley while the others remained stationary. Agassiz was of an inquiring turn of mind and was not satisfied with finding out merely that the glacier moved. He also measured the rate of movement of the glaciers on which he worked and demonstrated that the middle of the ice moved faster than the sides.

Forward movement of the ice near its margin at a rate of a few inches per day in the warm season is, perhaps, average and a movement of a

few feet per day is rapid. It is scarcely believable that with such slow movements a glacier can be a powerful agent of transportation and mechanical weathering.

EROSION BY GLACIERS

The former presence of a glacier in a region is recognized by the deposits that it left when it melted away. Such deposits contain almost incredible amounts of rock débris and such débris must have been picked up in some way and either carried or pushed along. One of our first studies of glaciers is concerned with the way in which they get their loads.

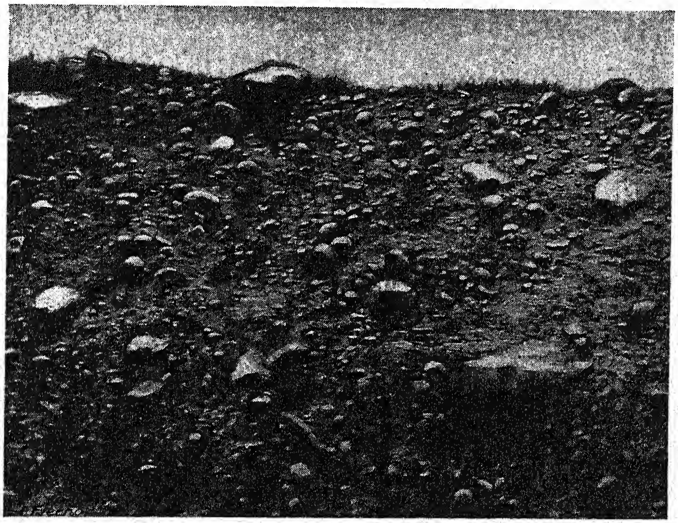


FIG. 249.—Glacial deposit showing variety in sizes of rock fragments. (*Photograph by E. B. Branson.*)

Getting a Load.—As the first snows that were to make a glacier fell, they rested upon mantle rock either residual or transported, probably in the main residual, *i.e.*, mantle rock that had resulted from the weathering of the underlying rock. Melting and refreezing took place frequently, the mantle rock came to have a cementing material of ice, and the projecting boulders and pebbles became frozen into the lower part of the ice. In addition to the rock material frozen in the bottom of the ice there are other rock materials throughout the entire ice mass. Even in the coldest regions the wind carries a certain amount of dust, and this falls with the snow. Where the snow melts, the proportion of dust increases and may form rather definite streaks in the ice. In some cases volcanic dust scatters widely over the snow surface and may even make beds of dust in the glacier. During the eruption of Katmai dust was blown on to several glaciers, in some places several feet thick.

The glacier finally becomes a mass of granular ice streaked here and there with dust layers. In valley glaciers another factor enters into

their composition. Formed in the bottoms of valleys, they have materials washed on to them from the sides while they are accumulating. During the summers the snow melts or rain falls and washes materials down the sides of the valleys and out on to the forming glacier, so that the valley glacier may have coarse material scattered through it almost from top to bottom. Some glaciers are in very steep-sided valleys and débris falls directly upon them from the cliffs. The thicker the valley glacier becomes the more nearly it fills the valley, the less likely it is to receive materials from the sides, and the cleaner the upper ice is compared with the lower. If one could observe a section of this newly formed glacier, he would see at the bottom mantle rock cemented with ice, above that, ice intermingled with rock débris of various kinds, and higher in the glacier mainly ice and some finer material.

A glacier is a mixture of ice, boulders, gravel, sand, and clay. As it starts to move, the mantle rock frozen into the bottom moves with it as part of it and forms a sort of rasp on the glacier bottom. The glacier advances on to more mantle rock, which it freezes to, picks up, and makes part of itself. However, in most cases it does not push that mantle rock out of place but in a sense creeps over the top of it. It is constantly melting near the edge and the water runs down, refreezes in the pore space of the mantle rock, and gradually picks it up. Many miles of the glacier may pass over the mantle rock before all of it is absorbed into the glacier bottom. After all of the mantle rock has become part of the glacier and the bare rock is exposed underneath, the rock-shod mass begins to scour fine material from the solid rock and pluck or break off projecting pieces. Imagine the effect of a mass of ice 2,000 or 3,000 feet thick, shod with sand, gravel, and boulders, moving slowly over a bare rock surface. Probably the effect is not so striking as one might imagine, as the glacier moves so slowly that the actual amount of down-scouring is small and the total effect is more like sandpapering in order to finish woodwork rather than like planing or chopping on the wood. The sharp gravel and boulders are pressed down hard enough to make scratches even in such rock as granite, and as the ice is moving in one general direction the scratches on the rock surface are nearly parallel. It is only relatively resistant rock that will take such scratches and retain them. In some places glaciers move over soft shales and other rocks that contain many cracks or joints and that are tilted so that the ice strikes the under part of the layers and tends to peel them up. In such cases great quantities of material are plucked and removed by the glacier and it may actually overload itself or pick up more material than it can carry.

How a Glacier Gets Its Load

1. It freezes to the mantle rock on which the original snows fall and makes that mantle rock part of the glacier.

2. It picks up more mantle rock as it advances.
3. It scours and plucks materials from the solid rock.
4. The winds blow material on it while it is forming and thus give wind material throughout the entire mass.
5. Particularly in valley glaciers materials are washed on to the top or slump on the top while the ice is moving and even while the glacier is decreasing in thickness as it moves forward.

CHARACTER OF THE GLACIAL LOAD

Drift.—Some parts of glaciers are nearly half composed of material other than snow and ice, while others contain only a small amount of foreign material. After a glacier has melted back and left its load on the ground, it is easy to examine the materials which it carried. In size these materials range from boulders 40 or 50 feet in diameter to clay particles. (Instances of masses several hundred feet in diameter are known). Boulders 40 to 50 feet in diameter are exceptional, but those 5 to 10 feet in diameter are by no means uncommon, and on first examination boulders 1 to 5 feet in diameter seem to make up the main part of the drift. *Drift* is a technical term used to designate all materials that have been handled directly or indirectly by the ice, and fine materials such as gravel, sand, and clay make up most of it. Much glacial drift is called *boulder clay* because it contains boulders in the midst of the clay. Glacial materials may be characterized as extremely heterogeneous in size.

The number of kinds of rock contained in glacial drift is surprising to students. Fragments of every kind of rock that the glacier passed over are in it. The larger boulders are made up of the harder rocks, such as granite, gneiss, quartzite, and the more resistant limestones; schists and the less resistant types of igneous rock are represented by gravels and finer fragments. The sands and clays are mainly from the weathered mantle rock that the glacier picked up.

Rock Flour.—Material scoured off the solid rock by the glacier is more characteristic of drift than the clay and fine sand from the weathered mantle, although not so large in amount. Glaciers powder minerals as they scour them and produce white material called rock flour. However, the scoured material does not appear white when mixed with the other fine material in the drift. It is colored by other fine material and it is impossible to distinguish such powdered material from the clays originating in the mantle excepting by microscopic examination and chemical tests. The fine material resulting from the chemical weathering is largely composed of clay minerals, while the fine material resulting from the glacial scouring is made up of a large variety of minerals but lacks clay minerals. This clay is not made up of as fine particles as the clay of the weathered mantle.

As the larger pieces of rock are moved along in the glacier some of them rub against the bottom and their sides become flat and scratched,

but they are likely to turn over after being moved along for a short distance and to flatten on another side. A considerable number of the boulders in the drift have such flattened and scratched surfaces and these are probably the most characteristic features of glacial boulders. As drift is dropped directly from the ice it is not sorted and so shows no stratification excepting where it is worked over by water. We may then add two more qualities characteristic of glacial drift, lack of sorting and stratification and the presence of flattened and scratched boulders. Glacial boulders are subangular, *i.e.*, almost angular, in contrast to stream boulders which are rounded.

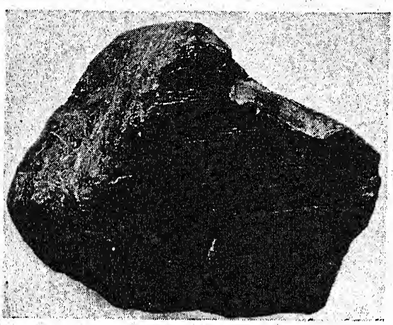


FIG. 250.—A glacial boulder showing flattened surface, scratches, and subangular shape.

Waters issuing from glaciers are likely to be milky-looking on account of the ground-up rock fragments which they contain. The milky nature of the water may persist for many days and even after the water has passed through several lakes which act as settling basins. It is only the extremely fine material that will stay in suspension for many days. The chemically weathered fine material is much less likely to give color to glacial water than the ground-up material or rock flour.

GLACIAL DEPOSITS

Glacial deposits are made up of materials that the glacier carried or pushed along and dropped at the edge, sides, or bottom of the ice. The deposits are called *moraines* and take their names from the place of deposition as *terminal*, *ground*, or *lateral*.

Terminal Moraine.—The materials piled up at the edge of a continental glacier or at the end of a valley glacier make terminal moraines. These form where the end or edge of a glacier remains stationary for some time, a condition resulting when the advance of the ice exactly equals the waste from melting and evaporation. That is, if the ice moves forward 5 feet per day and the edge melts back 5 feet per day, all the load in that 5 feet is piled up in one ridge. If such a condition should persist for 100 years, all of the load in more than 30 miles of ice would be piled up in one ridge. This ridge would be irregular in height and width.

Most terminal moraines are not such simple ridges. The ice edge does not remain stationary, but after forming one ridge may retreat slightly and irregularly, or not at all in some places, pile up a second ridge a few hundred feet back of the first ridge, and repeat the process many times. The irregular retreat of the edge may leave the ridges in contact at some places and a series of interlocking ridges results. The depressions

between the ridges become sites of small lakes and the highest parts in the ridges form conspicuous knobs.

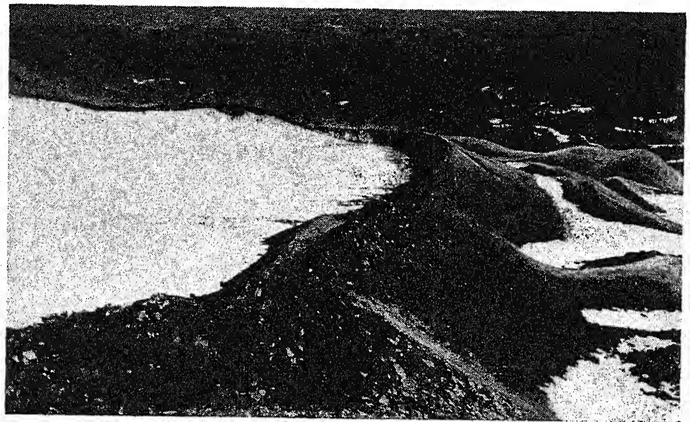


FIG. 251.—A glacier forming a terminal moraine. The edge of the glacier was at one time thick enough to project above the top of the moraine. (*Photograph by Russell. Courtesy of U. S. Geol. Survey.*)

Terminal Moraines of Continental Glaciers.—Few terminal moraines of continental glaciers are more than 50 feet high, most of them are made

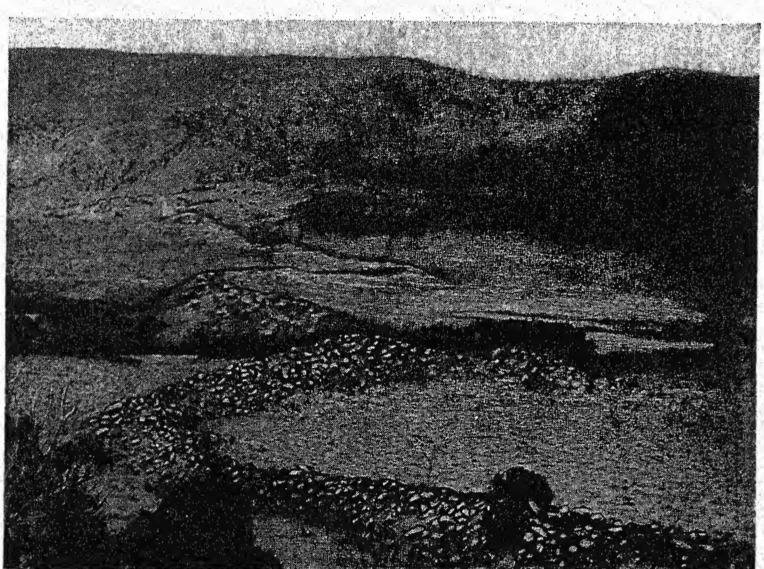


FIG. 252.—A simple terminal moraine in Bull Lake Creek Valley, western Wyoming. The moraine is about 1½ miles long and about 100 feet high near the stream. (*Photograph by E. B. Branson.*)

up of several ridges, and some are several miles wide. If the ice edge retreats slowly and builds up deposits back of the terminal moraine,

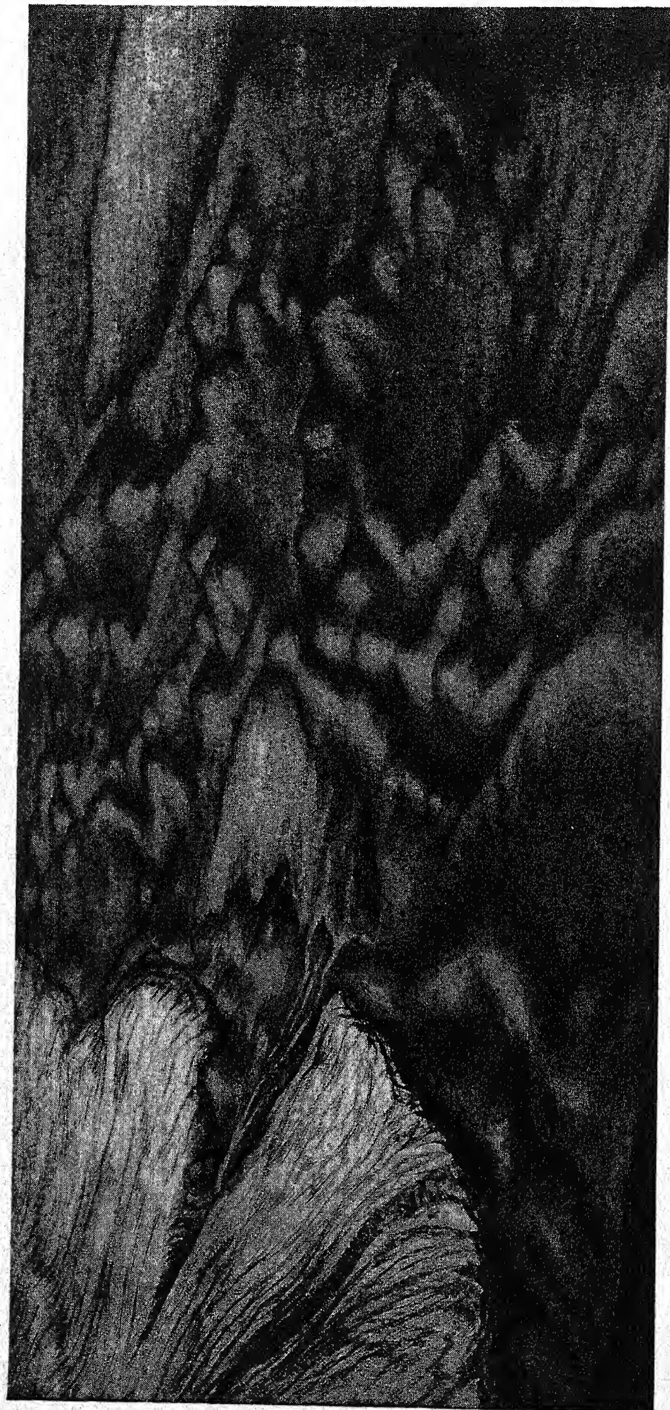


FIG. 253.—A terminal moraine made up of three or four interlocking ridges. The outer ridge was drawn to resemble Fig. 252. In the notch in the glacier a kame is forming. Depressions without outlets appear between the interlocking ridges. At the right of the moraine is an outwash plain.

there may be no sharp line of demarcation between terminal moraine and those deposits. A person crossing from one to the other might not notice any change.

A simple-ridge terminal moraine 50 to 100 feet high forms a conspicuous feature in otherwise rather level topography. The edge of the glacier was not stationary long in forming such a ridge and no thick alluvial apron formed in front. If the deposits back of the ridge are thin the moraine stands out nearly its entire height above the surrounding region.

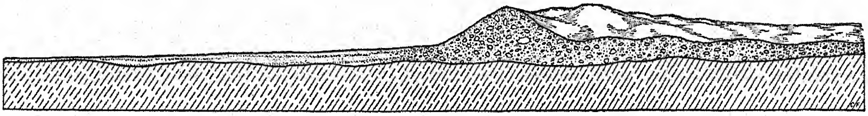


Fig. 254.—A section through ground moraine, high terminal moraine, and outwash plain.

A glacier may form many terminal moraines while its edge is retreating; the continental glaciers that covered the northern part of the United States formed hundreds of them. If, however, the edge of the ice advanced again, it passed over its own terminal moraines and either picked up the materials or spread them out to form ground moraines. There is no way of determining how many times some of these glaciers advanced and retreated and no way of telling how many moraines they formed.

Lateral Moraine.—Along the sides of valley glaciers material is deposited much as it is in the front, though as the edge does not fluctuate

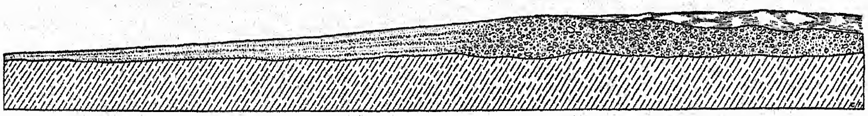


Fig. 255.—A section through ground moraine, low terminal moraine showing little or no relief, and outwash plain.

as much as the front a lateral moraine is likely to be made up of a single irregular ridge. In mountain valleys lateral moraines may appear like railway grades, ridges regular on top. They are discontinuous where the glacier moved through narrow places in the valley. Where a glacier has filled a valley the lateral moraine may appear on the margin. Valleys more than 1,000 feet deep may have such marginal moraines and this has given rise to the statement that some lateral moraines are more than 1,000 feet thick.

Ground Moraine.—The ground moraine occupies nearly all of the area covered by the glacier save the terminal moraine part. Much of the material of the ground moraine was deposited under the glacier as the bottom of the glacier melted or as the glacier became overloaded and rode over it. As the ice was very unequally loaded the ground moraine

in some places is thick and in other places thin or absent. The top of most ground moraines, however, was deposited in just the same way as the terminal moraines, *i.e.*, from the edge of the glacier as the glacier edge melted back and the materials were dropped. Consider a glacier advancing 1,000 feet per year and the edge melting back 2,000 feet. All of the load in 2,000 feet of the glacier would be deposited over 1,000 feet of the ground, and that would become ground moraine. Only in those places where great areas of the ice sheet stranded and melted down without the edge really melting back would the ground moraine all be deposited as from the bottom of the ice.

Topography of Ground Moraine.—The topography of the ground moraine is dependent largely on the topography of the land on which it was deposited. If ground moraine is formed on a nearly level surface,

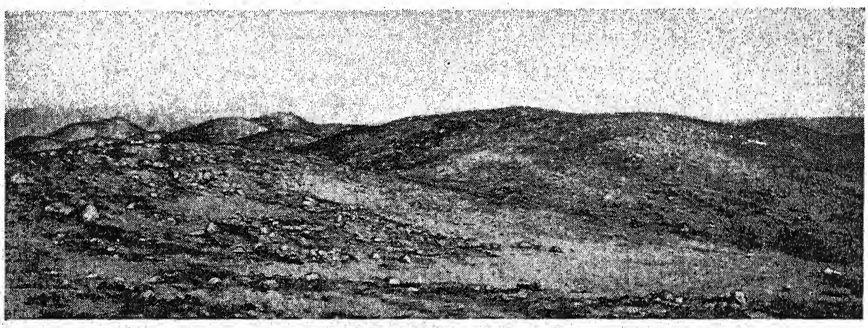


Fig. 256.—A small part of a terminal moraine. *(Photograph by E. B. Branson.)*

its topography is determined by the distribution of the load in the glacier. Where the load was large there are hills and where the load was small there are depressions, and the topography comes to consist of low hills unrelated to stream valleys, and shallow depressions without outlets. The shallow depressions may become the sites of lakes. Such topography is normally not very rough.

Drumlins.—In some areas when the ice was very heavily loaded, *drumlins* (drift hills) up to 150 feet high formed. These must have been deposited when the ice was nearly stagnant, but enough movement remained so that they were elongated in the direction of the ice movement. In parts of central New York and Wisconsin they are so numerous that the entire topography consists of drumlins and depressions between drumlins. The drumlins are all elongated in one direction and are rather remarkably uniform in size. Most of them are from ¾ to 2 miles long, ¼ to 1 mile wide, and 70 to 80 feet high. They are composed of ordinary glacial drift, and the materials are not stratified. Drumlins attract the attention of anyone interested in land surfaces, whereas the ordinary ground moraine is somewhat monotonous in its topography.

Ground Moraine over Rough Topography.—Where the glacier moved over a rough area, *i.e.*, one of mature topography, the distribution of ground moraine was controlled to a considerable degree by the topography. Valleys were filled or partially filled, the tops of the hills scoured off, and little or no morainic material left on them. The filling of the valleys in some places and partial filling in others left great numbers of depressions without outlets which were deep enough to become the sites of lakes. Most of the lakes of Wisconsin, Michigan, New York, Canada, and the New England states were formed in this way. Lake Chelan

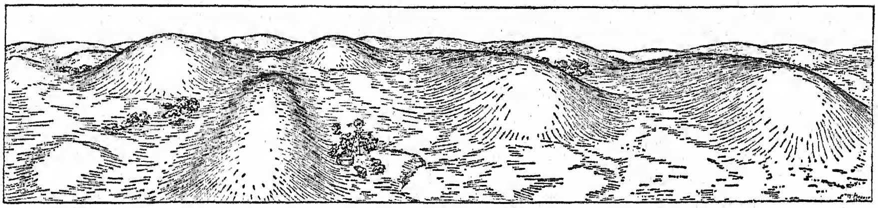


FIG. 257.—Drumlins viewed from the ends.

in Washington and the finger lakes in the central part of New York are striking examples of stream courses that were nearly parallel to the movement of the glacier and were scoured decidedly but not filled very much. Where glaciers moved across valleys they made irregular deposits and created many lakes.

Glacial Drainage.—Continental glaciers, such as those that occupied North America to as far south as the Ohio and Missouri Rivers, had a great deal of water running over them, through them, and underneath them. In the southernmost 300 or 400 miles melting must have equaled

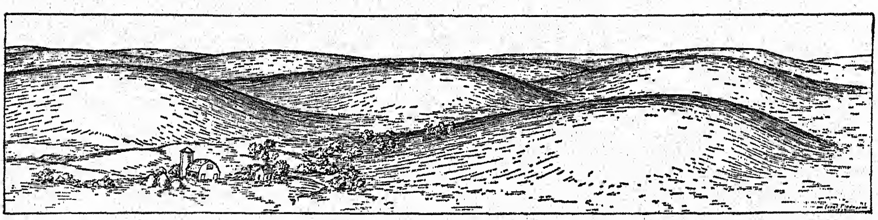


FIG. 258.—Drumlins viewed from the sides.

or exceeded snowfall and the glacier was gradually decreasing in thickness southward. It was supplied from the north with thousands of feet in thickness of ice; by the time its edge reached the Ohio River it was only 200 or 300 feet thick, but it also received the snowfall and rainfall of the regions over which it came. It therefore lost several thousand feet of ice through melting; also, there ran over it and under it the water from the snowfall and rainfall of the region. As the ice of glaciers is cracked and porous, large streams cannot form and exist for a long time on the top and most of the drainage is in subglacial streams.

Stratified Drift.—The water under the ice ran through and over great quantities of loose material. It worked over some of the loose material and partially stratified it, sorted out the fine material and carried it on and left the coarser material behind, thus creating patches

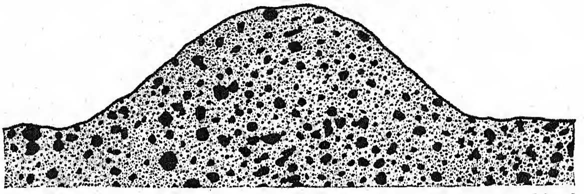


FIG. 259.—Section of a drumlin showing unstratified drift; coarse pieces black; fine particles white.

of partially sorted gravel. In addition to patches of stratified drift, two distinct topographic features, eskers and kames, formed of stratified drift.

Eskers.—Glacial streams running in channels under the ice or in fissures in the ice may be so heavily loaded that they block their own channels with gravel but carry the sand and clay to the edge of the glacier. If they block their channels at the time when the ice is practically stag-

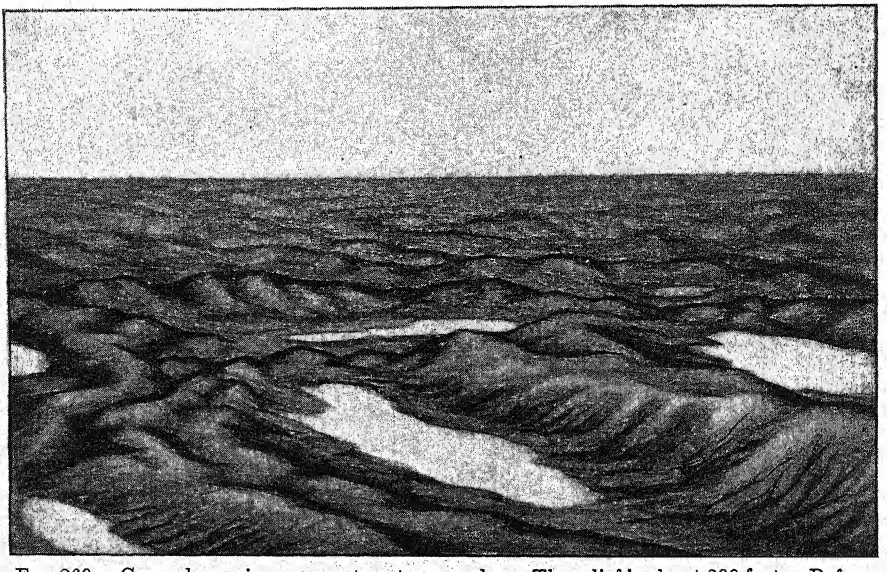


FIG. 260.—Ground moraine over mature topography. The relief is about 200 feet. Before glaciation, this topography was that of Fig. 117.

nant because of having melted down to insignificant thickness, the deposits are in ridges, something like railway grades, running in the same direction as the ice movement. Such ridges, called *eskers*, are not common features, as most of them are destroyed by ice movement about as soon as they form and they can be preserved only when the ice move-

ment is insufficient to destroy them. The gravels are really stream deposits and are rudely stratified.

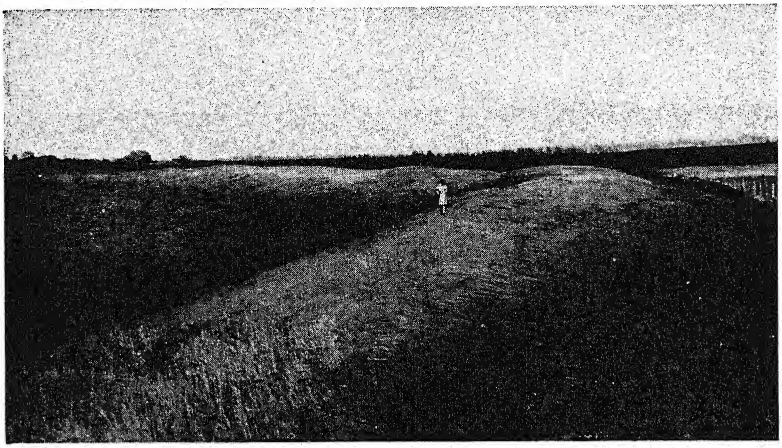


FIG. 261.—An esker. (*Photograph by I. C. Russell. Courtesy of U. S. Geol. Survey.*)

Kames.—The subglacial streams loaded themselves heavily with gravel and sand. They also came in contact with the larger materials, but sorted them out, left the boulders behind, carried the clay, sand, and

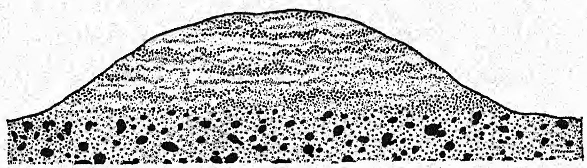


FIG. 262.—A cross-section of an esker showing stratified sand and gravel. The esker was formed on unstratified drift.

gravel forward, and sorted them one from the other. Such a stream, emerging at the edge of the ice, melted the ice above it and so formed a canyon with ice walls just back of the ice edge. It proceeded to fill the

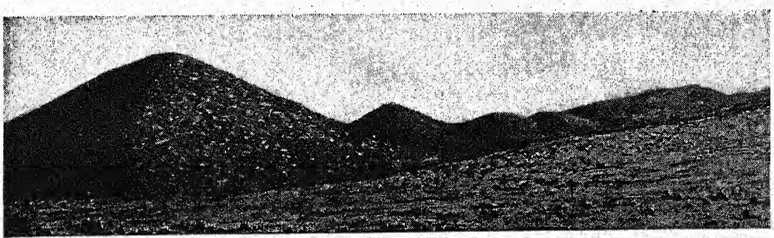


FIG. 263.—A kame and part of a terminal moraine. Few kames are as symmetrical as this one. Height nearly 200 feet. (*Photograph by H. L. Griley.*)

canyon with gravel and carried the sand and clay forward and deposited them beyond the terminal moraine. The water finally found a new

outlet and abandoned the canyon which it had filled with gravel. After the ice had melted and left the terminal moraine disconnected with the glacier itself, the gravel in the ice canyon became an unusual feature, both topographic and structural, of the terminal moraine. It formed a hill of sorted gravels, rather than of heterogeneous material of all sizes, in the back edge of the terminal moraine. Such hills of sorted gravels have been called *kames*. Many kames are not in the back part of moraines, as, after they form, the edge of the ice may retreat a little and build another ridge back of the kame. If a kame had formed next to the outermost edge of the Bull Lake moraine described on page 247 and all of the other ridges had been built back of it, the kame would really be in front of the main part of the moraine.

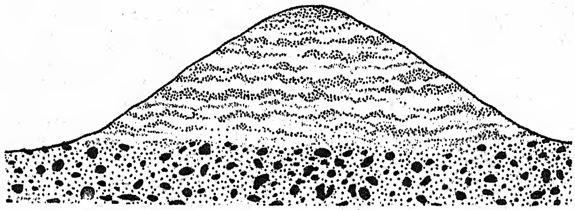


FIG. 264.—Cross-section of the kame shown in Fig. 263 indicating stratification of materials in the kame and the unstratified drift below the kame.

Use of Glacial Gravel.—The gravels from both eskers and kames have been used extensively as road metal and ballast for railroads. It is fine enough to be used directly on roads without sifting, and makes cheap and very good road material. It is cheap because it may be taken out with a steam shovel and does not need to be crushed, and good because it is composed of the more resistant materials carried by the glacier and sorted out by the streams. If the glacier moved only over sandstones and shales, it would not furnish good gravels, but the glaciers of North America moved over great areas of igneous and metamorphic rocks and thus secured granites, diorites, gneisses, schists, and quartzites, as well as limestones and sandstones.

Outwash Plains.—As the terminal moraine formed a great deal of water ran over the top down through the main mass and out from under the ice. Part of the water was organized into streams and part was merely unorganized run-off. With the loose material of ground and terminal moraine available each little stream loaded itself heavily and built a small alluvial fan against the terminal moraine where its velocity decreased. As the alluvial fans grew laterally, they united and formed a sort of outwash apron which sloped gently away from the moraine and which was built up nearly as high as the moraine itself at the part which connected with the moraine. This is called the *outwash plain*, and where nearly as high as the terminal moraine makes the moraine inconspicuous on its side away from the ice.

One might then approach a large terminal moraine from the unglaciated side, go over it, and down on to the ground moraine on the other side without being aware that he had crossed any ridge-like topographical feature (see Fig. 255). On the other hand some moraines are conspicuous, containing hills that rise far above the surrounding region and may be seen for miles. Where the terminal moraine is inconspicuous as a topographic feature, one may recognize it by the *kettles*, or deep and narrow depressions without outlets, which may be occupied by small lakes, and by the knob-like hills between kettles. The kettles might be mistaken for sink holes but may be readily distinguished by bouldery material on their sides and by the lack of solid rock near them. Most of them are larger than sink holes and their margins are less sharply defined.

Summary of Characteristics of Drift

Heterogeneous in size of materials, huge boulders to clay.
Heterogeneous in kinds of materials, all kinds of rocks that the glacier passed over.
Many of the boulders are subangular.
Many of the boulders have flat faces.
Many of the boulders, cobbles, and pebbles have scratches on them.
Not stratified excepting the minor parts deposited by water.
Some of the fine materials are nonchemically weathered rock flour.
Boulders may be embedded in clay and sand several feet from other boulders.

In some cases it is difficult to distinguish glacial drift from bouldery stream deposits. Lack of good stratification is also characteristic of the coarser deposits of alluvial fans, although even there some stratification appears. Swift streams move materials as large as some of the large boulders of glacial drift. The geologist examines the boulders of the deposit for flattened sides and scratches on flat surfaces, but in greatly weathered drift he may not find these qualities. The best distinguishing feature is the sorting of materials coupled with stratification. Most drift has boulders and cobbles well separated by clay, while in stream deposits boulders and cobbles touch one another and are not separated by clay and sand.

PLUCKING AND SCOURING BY GLACIERS

Factors Influencing Rate of Erosion by Glaciers.—On account of their great weight it seems that glaciers should be powerful plucking and scouring agents, but such eroding power depends on several qualities, of which thickness of the ice or weight is important. Rate of movement is very important, and as the ice moves slowly, its plucking and scouring power is small compared to its weight. A glacier heavily shod with hard rock erodes faster than one with little load. Plucking and scouring are faster on rough surfaces than on smooth if the roughness is not so great as to retard motion. Both reduce soft rocks much faster than hard, and

shale is cut down several times as fast as granite. Rocks that are slightly dipping in the direction of ice movement are plucked much faster than horizontal beds or those dipping up-movement. Rocks that are closely jointed are plucked much faster than rocks with widely-spaced joints, and thin-bedded rocks faster than thick-bedded.

Cirques.—Deposition by glaciers is of much greater importance than plucking and scouring but some erosional features produced by wear are conspicuous and many are important. Near the tops of mountains at the heads of mountain glaciers the ice scours directly downward and forms steep-walled, somewhat circular depressions open on one side, known as cirques. Some such depressions have walls more than a thousand feet high, and they are the most conspicuous topographic features of moun-

FIG. 265.—A cirque in Wind River Peak, Wyoming. (*Photograph by E. B. Branson.*)

tains that have been intensely glaciated. The Uinta Mountains of northern Utah contain numerous large cirques although the glaciers that formed them have long since disappeared.

U-shaped Valleys.—As valley glaciers move down mountain valleys they modify by scouring the irregularities formed by streams and change the narrow-bottomed valleys to wide U-shaped valleys. The valley shown in Fig. 267 has not been glaciated. It was formed in the same rock formations in the same mountains by a stream about the same size as the valley of Fig. 266. By comparing these you will see that the glaciated valley is of much greater width and more rounded at the bottom. Some of the material scoured off to form the U-shaped valley from the V-shaped has gone to make rock flour, and some was plucked off and formed boulders, cobbles, and pebbles.

Unlike streams, glaciers may scour upstream places deeper than downstream and thus create rock basins in their valleys. Such rock

basins are rarely deep and most of the lake basins of glaciated valleys were not formed by scouring but by deposition. Projecting knobs of rock are likely to be smoothed and scratched by glaciers. Granite areas

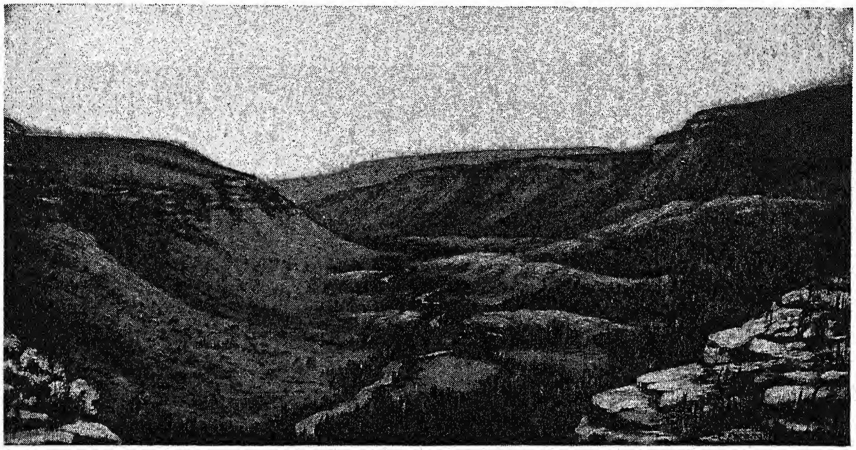


FIG. 266.—Big Popo Agie Valley, about 12 miles south of Lander, Wyoming. A U-shaped valley about 800 feet deep. The ridges across the valley are terminal moraines but they are so far away that they are inconspicuous. (*Photograph by E. B. Branson.*)

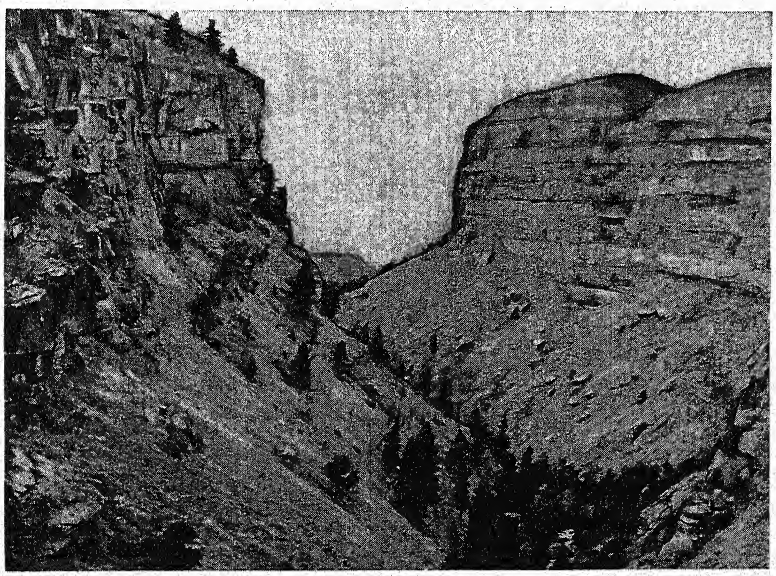


FIG. 267.—Little Popo Agie Valley about 10 miles from the valley shown in Fig. 266. Both valleys were formed by streams of about the same size and both were cut in the same kinds of rocks. Glaciation caused the differences in shape. (*Photograph by E. B. Branson.*)

that have been glaciated are so smooth as to make walking over them hazardous. By walking from nonglaciated granite to glaciated one would be able to tell the difference by the rough footing in one and the

smooth in the other. In the Alps, where glaciers have moved through valleys composed of dolomite, they have scoured off the small knobs, leaving conspicuous small oval hillocks. From a distance these look like flocks of sheep and the natives call them sheep rocks, "roches moutonnées."

Hanging Valleys.—Some valley glaciers have scoured their valleys much deeper than the streams left them. A valley heading in the mountains is filled with ice far below the snow line, but the tributary valleys below the snow line contain no glaciers and those above the snow line are likely to have glaciers with less scouring power than the main

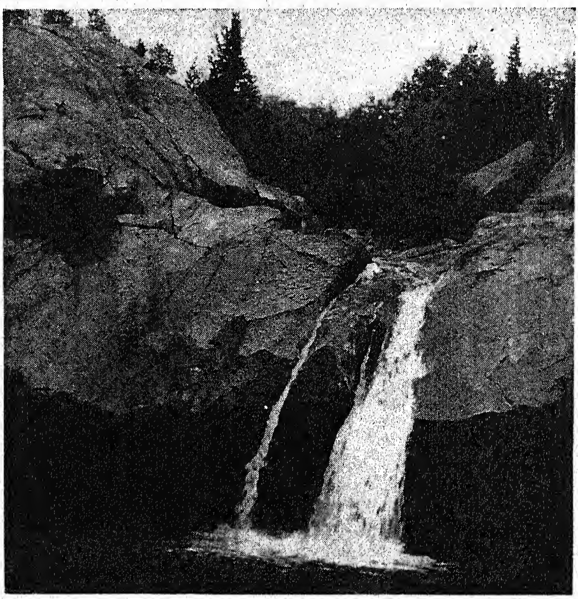


FIG. 268.—A hanging valley on the side of the valley shown in Fig. 266. (*Photograph by E. B. Branson.*)

glacier. The tributary valleys are not deepened so rapidly as the main valley, and after the glacier recedes their waters fall over cliffs where they enter the main valley. These are known as *hanging valleys*, have waterfalls in early stages, and are one of the evidences of former glaciation.

Scouring by Continental Glaciers.—Scouring accomplished by continental glaciers is less conspicuous than that by valley glaciers. The covering of mantle was so great that most continental glaciers did the greater part of their work in merely removing it. Where a glacier crossed a wide valley, it might do considerable scouring as it moved up the far slope. The summits of ridges between deep valleys, the tops of hills, and level places where there was only a small amount of mantle rock were scoured by the continental glaciers of North America. When one imagines ice thousands of feet thick over most of the northern part of

North America, and that ice in steady motion, he is likely to assume that all of the country was deeply eroded by it. However, the average depth

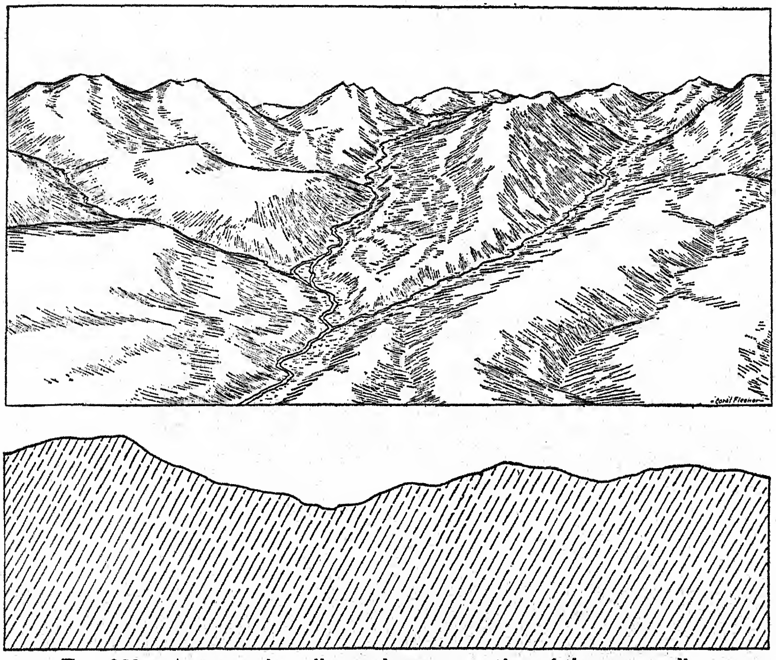


FIG. 269.—A mountain valley and a cross-section of the same valley.

of the morainic material over the area covered by the continental glacier is less than 20 feet. The average depth of mantle rock outside of glaciated

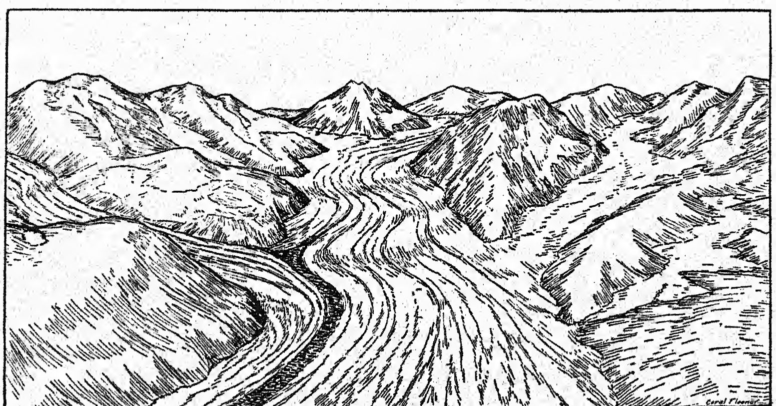


FIG. 270.—The valley shown in Fig. 268 filled with a glacier.

areas is about 10 feet. As the glaciers must have handled the mantle rock, the total amount of erosion or downward cutting by them was probably not more than 10 feet.

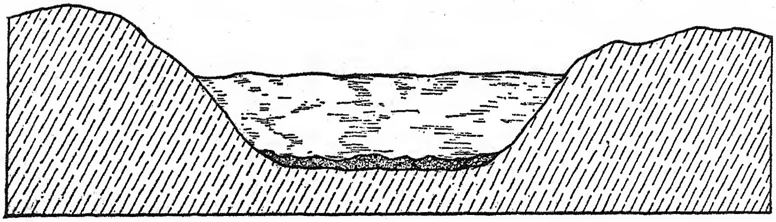


FIG. 271.—A cross-section of the glacier-filled valley shown in Fig. 269.

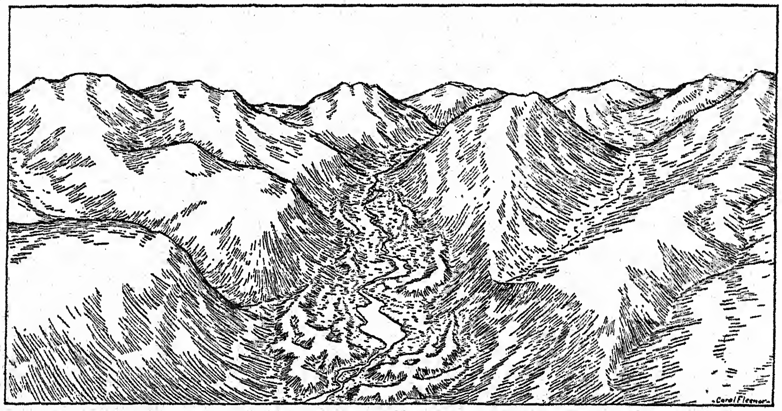


FIG. 272.—The same valley shown in Fig. 269 after the glacier had disappeared. A hanging valley on the right.

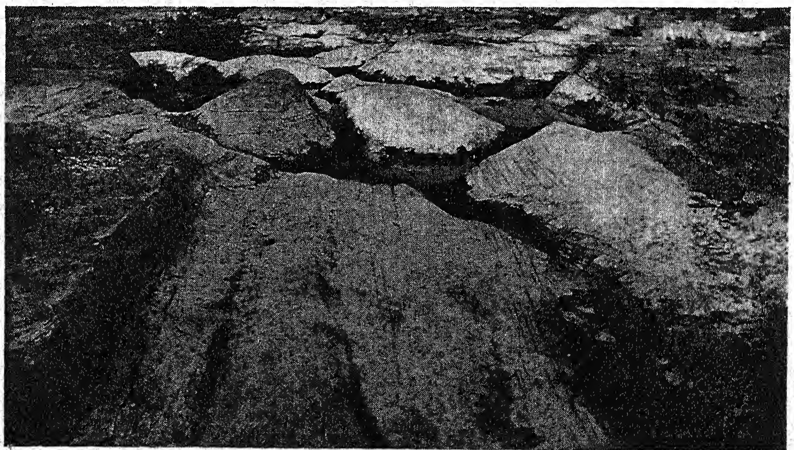


FIG. 273.—Glacial gouges and scratches on limestone, Kelleys Island, Lake Erie. (*Photograph by H. E. Wilson.*)

Glacial Scratches on Bedrock.—Glaciers leave numerous subparallel scratches on the bedrock over which they move. If not covered with mantle rock, these weather off within a few hundred years or within a few thousand at the most. Scratches that may be seen as remnants of the work of the continental glaciers of North America, which disappeared 40,000 or 50,000 years ago, have had glacial drift over them that has been removed recently. The sides and bottoms of glaciated valleys are likely to show longitudinal troughs with scratches in them. The troughs may appear like the work of a carpenter who planes a deep groove and then sandpapers it smooth.

GLACIAL FEATURES IN ONE VALLEY

Considering only the scouring and plucking in mountain valleys gives one a wrong impression of the appearance of a glaciated valley. One may travel up such a valley from the end of the old glacier to near the source without noticing any conspicuous feature produced by glacial scouring and plucking. Most of such features, excepting the cirque, are likely to be covered with deposits made by the glacier. If one starts up a glaciated valley, the first feature that attracts his attention is the terminal moraine. This may be of the simple ridge type or of interlocking ridges. A description of one glaciated valley that displays all of the ordinary features of glacial deposition and glacial erosion may present a better picture of such features than generalizations can give. Such a valley is that of Bull Lake Creek, a tributary of the Big Wind River, about 100 miles south of Yellowstone Park. The outer part of the terminal moraine of this valley is on the banks of Big Wind River. The terminal moraine is about 3 miles from the outer side to the inner and is made up of an intricate network of some 25 interlocking ridges, part of which are shown in Fig. 256. The edge of the ice must have shifted 25 or 30 times while the moraine was forming. Isolated hills rise 100 to 200 feet above the deepest depressions. Depressions ⅛ mile across and 100 feet deep are present and much shallower, smaller depressions are common. Some ridges are distinct for half the length (distance along the ridges from one side of the valley to the other) of the moraine.

Glacial Dams.—The moraine formed a huge dam across Bull Lake Creek and created a lake basin. The stream has cut through the moraine to some 50 feet below the general level but the lake is still 8 miles long. The final ridge built by the glacier in this moraine is more than ¼ mile up the valley from the rest of the moraines and it cuts the lake nearly in two. From the ends of the terminal moraine lateral moraine ridges project up the sides of the valley at the valley margins. The glacier filled the valley to overflowing and built its lateral moraines on the extreme edge. The valley is 1,000 feet deep and the lateral moraines form the uppermost 100 feet or so of the margins.

From the terminal moraine one may travel upstream 8 miles before encountering any other conspicuous glacial feature. Boulders of various types are scattered over the valley floor but these might have been

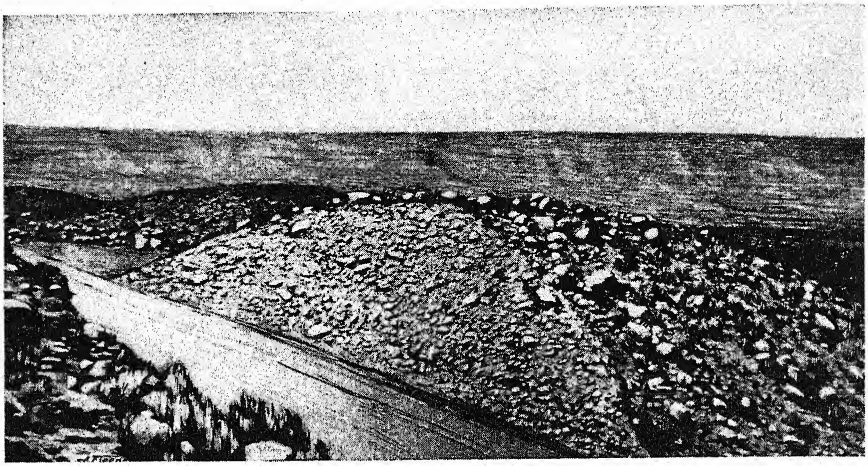


FIG. 274.—The terminal ridge of the moraine in Bull Lake Creek Valley, cut by a highway. (*Photograph by E. B. Branson.*)

brought in by the stream. A simple ridge, shown in Fig. 252, stretches across the valley 8 miles upstream from the terminal moraine. The ridge is about 100 feet high and about 1½ miles long from one end to the

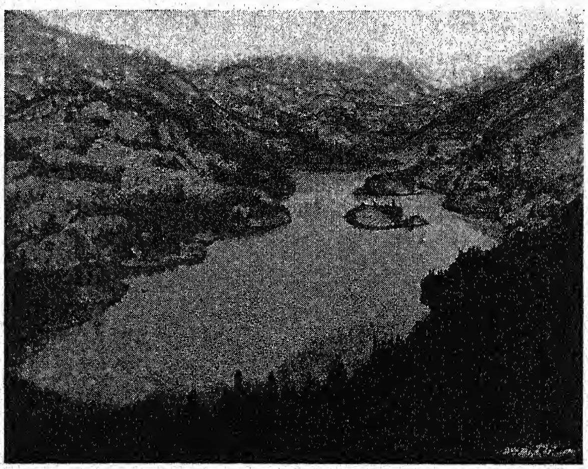


FIG. 275.—A glacial lake in Fremont Peak at the head of Bull Lake Creek, Wyoming. (*Photograph by E. B. Branson.*)

other. The edge of the ice must have remained stationary for a long period of years to produce such a ridge, which is in no way different from the ridges of the terminal moraine excepting in its simplicity. You may

consider this as the simplest type of terminal moraine although by no means the smallest. This moraine once shut in a lake but the stream has cut through the moraine and drained the depression. A short distance above the simple moraine one comes to granite and the valley takes on an entirely different aspect. It is deeper and narrower and has been less affected by glaciation, although the granite has been conspicuously smoothed. Glacial scratches appear in only a few places on the granite, as they have been obscured or completely removed by weathering. Weathering has not roughened the surface to any appreciable degree.

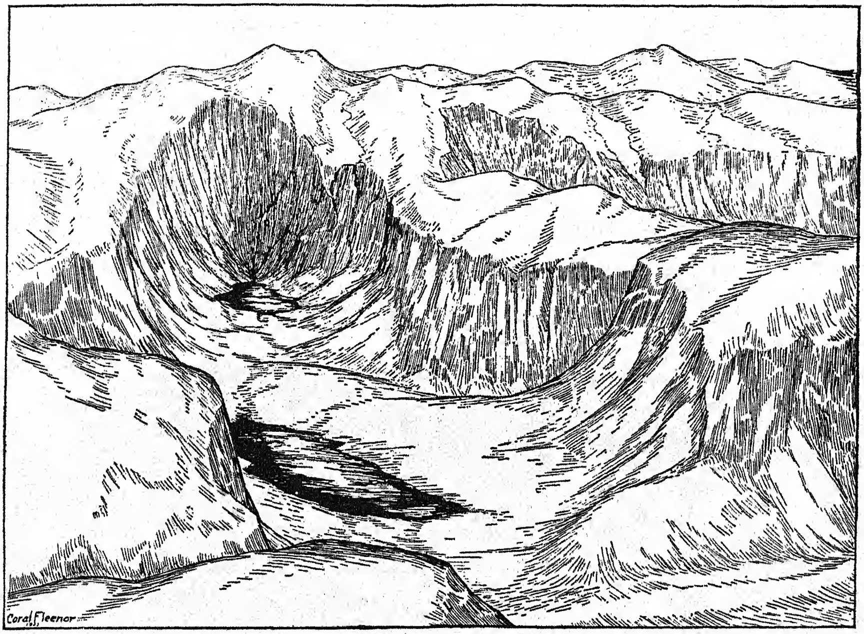


FIG. 276.—Drawing of a cirque, the highest walls about 800 feet.

Up the valley are numerous lakes, most of them shut in by small moraines, but a few basins were scoured out of the granite.

Cirques.—One finally comes to the glacier itself, 4 miles long and at the very top of the mountains save for a few projecting peaks and ridges. The glacier comes from a huge cirque. In this part of the mountains cirques are not conspicuous, on account of being filled nearly to the rim with snow and ice. Forty miles south, in the same range, the cirques are conspicuous, as the glaciers have disappeared. Where the glaciers are gone the top of the mountain remains as a narrow, sharp-crested, discontinuous ridge. The heads of glaciers have worked backward from either side, cutting the cirques further and further and finally having only a narrow ridge between. This type of topography can be seen only at the tops of strongly glaciated mountains. A road across the Uinta

Mountains passes near several large cirques where a narrow ridge remains between the cirques on the north and those on the south.

DRIFT WITHOUT GLACIAL TOPOGRAPHY

In northern Missouri a considerable amount of glacial drift occurs, in places 50 feet thick, but glacial topography cannot be identified. In going northward from Missouri through Iowa one travels continuously over drift and finally comes upon topography of terminal- and ground-moraine types made up of drift that is indistinguishable from the drift in Missouri. The drift in Missouri was deposited by a glacier that had

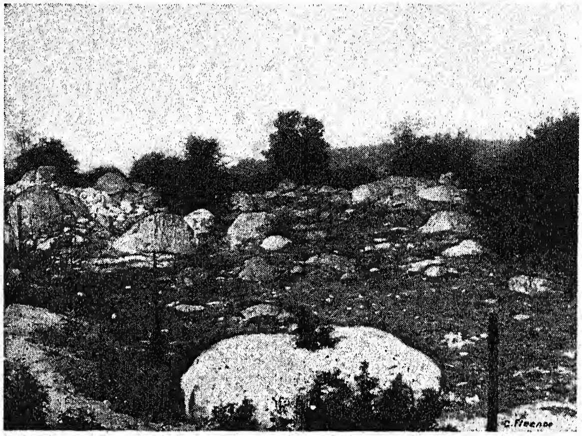


FIG. 277.—A boulder-strewn field. The boulders are erratics of limestone. (*Photograph by W. A. Tarr.*)

withdrawn, perhaps hundreds of thousands of years before a new glacier advanced into Iowa and formed the new deposits which show glacial topography. In the meantime streams had cut valleys through the Missouri drift and had destroyed all of the features of glacial topography. Since the time of the advance of the ice to form the Iowa drift the amount of erosion has been so small as to leave most of the glacial features.

SOLID-ROCK DRIFT OR TILLITE

A geologist working north of the Great Lakes in Canada found a place where a stream had cut down several hundred feet in solid rock, and after examining the rock carefully he decided that it had originated as a glacial deposit.

A glacier of one of the earlier geological periods had formed the deposit and the material had been cemented later to form solid rock. Such solid-rock drift has been found in many places in the world. Some of it is among the oldest of the sedimentary rocks and indicates that glaciation started at a very early period in the earth's history. This is

evidence that the earth has not been growing colder gradually but has had periods of cold followed by periods of warmth.

Destruction of Glacial Lakes.—In looking at a map of North America one is struck by the great number of lakes present in Canada, the northern middle states, the northern central states, and New England. With all the lakes plotted it might seem possible to draw the line between the glaciated part of North America and the nonglaciated part from the lakes alone. However, the line would be far from accurately drawn, for, as explained in an earlier paragraph, some of the glaciation was much older than other, and stream topography superimposed itself upon glacial topography and reduced the areas to mature topography in terms of stream erosion. Mature topography has all upland in slopes, and has no place for lakes excepting along the flats of the river bottoms. The glacial lakes disappear before full maturity is attained. Many glacial lakes fill up with sand and clay brought in by streams, by slope wash, and to a minor extent by wind.

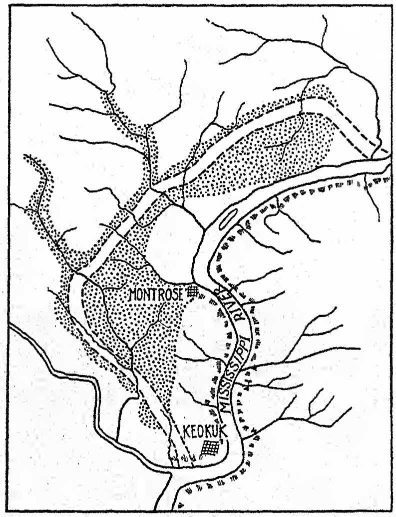


FIG. 278.—Map of Mississippi River between Montrose, Iowa, and Keokuk, Iowa, showing drainage changes. (*Modified from Leverett.*)

CHANGES IN DRAINAGE EFFECTED BY GLACIATION

Changes of drainage resulting from glaciation have been mentioned in a former paragraph but need to be emphasized further. In all of the glaciated areas valleys occur which are inconsistent within themselves, *i.e.*, they may have wide flats for considerable distance and narrow immediately to valleys not much wider than the stream itself. The Mississippi between Montrose, Iowa, and Keokuk, Iowa, is an example. On examining the region the geologist finds that the stream has a wide flat in its preglacial valley and that its valley is narrow where the preglacial valley was filled with drift and the stream forced to take a new course, probably over hard rock. Such changes of drainage are likely to cause falls and rapids, and the falls of the New England states and of New York (Niagara as the most conspicuous example) are due largely to the changes in drainage caused by glaciation.

After glaciation streams may flow on hard rock in areas where normal courses would be on soft rock or on unconsolidated clays and sands; they may flow long distances at low grade where under usual development they would flow short distances at high grade.

Economic Effects of Glaciation.—Glaciation has had profound effects on the habitability of many parts of the earth. In some regions it has smoothed the topography and made the land more suitable for agriculture; in others it has produced such roughness as to make the land useless for all but grazing purposes. In some areas it has enriched the soil by mixing together ingredients most needed by plants; in others it has piled nonproductive clay, gravel, and boulders on soils that had been rich. Glaciation has been largely influential in making New England a manufacturing region by creating abundant water power. In some places

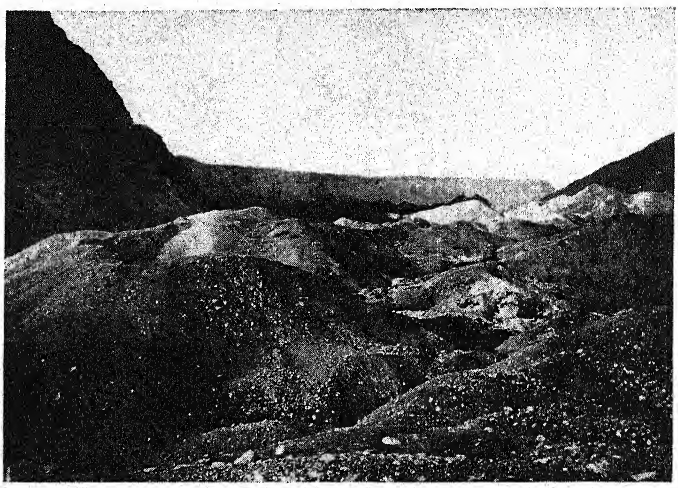


FIG. 279.—A valley filled with terminal moraine so that it might force a river to change its course. (*Photograph by Frank Charles Schrader. Courtesy of U. S. Geol. Survey.*)

rich ore and coal deposits have been covered so deeply with drift that their exploitation has been made difficult if not impossible.

THE THEORY OF CONTINENTAL GLACIATION

At this time it seems incredible that anyone could account for erratic boulders, scratched boulders and pebbles, scratched solid rock, and great deposits of drift in any way excepting by glaciation. However, it is worth recalling that in the early part of the nineteenth century, when observations of such phenomena were in their youth, the principle that "the events of the past are to be interpreted on the basis of the present" was not generally accepted and fanciful explanations of natural phenomena were common.

A geological book[1] published in the United States in 1889 stated that "there are probably no evidences of glacial action upon the continent of North America where they do not now exist, except in a few places in the Rocky Mountain region," but this book was about the last of its kind.

[1] MILLER, S. A., "North American Geology and Paleontology."

A supposition that all of northern North America was covered with water and that floating ice carried out the drift was not recognized as impossible by some theorists.

The conception that much of the north temperate region of the world had once been covered by glaciers was of slow growth even after the idea was promulgated. Louis Agassiz, whose measurement of glacial motion has been mentioned in a former paragraph, was responsible in the main for the acceptance of the continental glaciation hypothesis. After studying the movement of glaciers and some of the deposits at the lower end of glaciers in the Alps he traveled northward to find how far the Alpine glaciers had extended at an earlier period. After passing the last terminal moraines he continued northward for a long distance without seeing any evidences of glaciation and finally came again to terminal-moraine topography with the boulders of ordinary glaciation scattered over it. As he had crossed a considerable region where no glacial boulders and no glacial topography existed between this topography and the Alps, he knew that these moraines had not been formed by Alpine glaciers. As a matter of fact they could not have been formed by any glaciers from the south, and there were no mountains to the north sufficiently high to have accounted for the formation of Alpine glaciers. After he had found that these moraines covered wide areas he came to the conclusion that a continental glacier coming from the north had once covered the region.

This seemed a very fanciful and even impossible hypothesis and it was not accepted immediately by geologists or other scientists. If it had not been that Agassiz was a well-recognized zoologist and paleontologist, he would not have had the opportunity to present his ideas about glaciation as convincingly as he did. He was invited to go to England to give a series of lectures on zoological subjects, and while he was there some of the local geologists accompanied him into the field and found, even there, boulders and other evidence of glaciation that had escaped the attention of the local workers. He succeeded in convincing some of the geologists that his hypothesis was, at any rate, worth investigating. In America some geologists accepted the idea of continental glaciation with enthusiasm, whereas others would have nothing to do with it. Agassiz welcomed the opportunity to come to America and examine the materials that had been identified as glacial drift and to help with the establishing of the theory of continental glaciation. He became professor of zoology in Harvard University and was one of the most influential scientists in America during his lifetime.

CHAPTER XII

THE WIND

Wind is air in motion. Although air is only about 1/800 as dense as water, the wind possesses remarkable ability to accomplish gradational work. The degree to which the wind is effective depends upon its velocity. Large quantities of fine earth materials are moved far and wide by the wind. A complete study of the atmosphere would include many factors, such as climatic effects and temperature, but we are primarily interested in the air as a geological agent.

Wind Velocities and Resulting Pressures.—Velocities of the different types of winds are shown in the following table.

Type of Wind	Velocity, Miles per Hour
Light to gentle breeze	1 to 9
Fresh breeze	10 to 14
Strong wind	15 to 22
High wind	23 to 30
Gale	31 to 40
Strong gale	41 to 60
Hurricane	60 and above

When wind attains a velocity of 70 miles per hour, it sweeps everything before it. Hurricanes that have occurred in Florida and Puerto Rico in recent years are reported to have reached velocities of 125 to 150 miles an hour. The highest wind velocity so far (1934) reported in the United States is that of 164 miles an hour, which was recorded in April, 1933, at the observatory on Mount Washington, New Hampshire.

Winds of the higher velocities exert great pressure on the sides of buildings and are capable of demolishing most structures. The following table from Milham's "Meteorology" gives the pressure exerted by the wind at different velocities.

Velocity, Miles per Hour	Pressure, Pounds per Square Foot
5	0.12
10	0.50
15	1.12
20	2.00
25	3.12
30	4.50
40	8.00

50	12.50
60	18.00
70	24.50
80	32.00
100	50.00
125	78.12
150	112.50

THE GEOLOGICAL WORK OF THE WIND

The gradational work of the wind is accomplished essentially by *mechanical* means, though the air aids indirectly in accomplishing a certain amount of *chemical* work, also, which has been fully discussed under Weathering.

Mechanical Work

We are all familiar with the ability of the wind to do mechanical work, for we have watched it whirl leaves and paper about, felt it drive dust in our eyes, and probably felt the sting of sand grains driven against our faces. Just as with the other physical agents, the first step in the accomplishment of work by the wind is *getting a load*, then *transporting* it great or small distances, and finally *depositing* it.

Getting a Load.—The ability of the wind to pick up loose particles is due to eddies and cross currents produced in the air by objects on the surface. Whenever the currents are directed downward to the surface, they disturb loose material and, if the particles are small enough to be lifted, cause its upward deflection into the air.

Loose Material on the Surface.—The immediate source of a load for the wind is the loose material (soil) of the surface. The dry surface of a plowed field, the flood plain and channel of a river, a beach, a dried-up lake or playa, a desert area, a gullied hillside, or any other surface unprotected by vegetation or not continuously moist furnishes material for the wind to pick up.

Abrasion.—The wind secures a part of its load, however, by greater efforts than those of merely picking up loose material. This is by the abrasion of the surface over which it moves. To accomplish this, the wind must of course have tools, *i.e.*, something it can drive against a rock to grind off particles. Its chief tools are the dust and sand particles it has picked up from the loose material on the surface.

Most of the abrasive work is done by driving sand grains against a surface, the finer dust particles being of use chiefly in polishing the abraded surface. For the most part the particles worn off are small (of dust size) and are immediately swept away by the wind. A part of the material may be sand, however, as, for example, the grains furnished during the abrasion of a sandstone. The cement of the sandstone usually wears away first, so the sand grains are free to be picked up by the wind.

During the process of eroding a surface the tools of the wind, *i.e.*, the sand grains, also become worn. The original sand grains may have been angular but soon their corners are worn off and finally they are reduced to well-rounded grains (see Fig. 189, page 176). The wind can form perfectly rounded sand grains of quartz to sizes as small as 0.15 millimeter in diameter, which is about one-fifth the size of the smallest grains that can be rounded by water. The constant chipping off of small bits from the surface of a sand grain leaves it minutely pitted, with a consequent frosted appearance.

Injected Material.—Although most of the load of the wind is acquired by its own efforts, occasionally material is injected into it. Vast quantities of volcanic dust have been blown into the atmosphere by violent

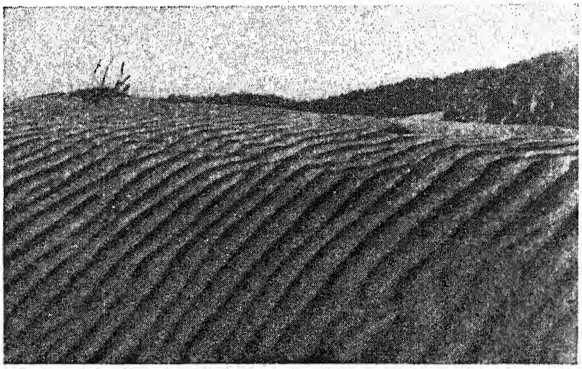


FIG. 280.—Current ripple marks made by wind in volcanic ash, Irazu, Costa Rica. (*Photograph by E. B. Branson.*)

volcanic eruptions, of which the Krakatoa explosion is an excellent example (see page 38).

Summary.—The wind gets its load by first picking up material it finds loose on the surface and, then, the material it has eroded by using the first material as tools. Additional materials are contributed to it during volcanic eruptions.

Transportation.—The wind transports material in three ways: by *rolling*, by *jumping* or *saltation* (*i.e.*, moving the material along the surface in a series of short jumps), and in *suspension*.

Rolling.—The major portion of the larger grains carried by the wind are rolled along the surface. A wind that moves straight forward is favorable to this method of transportation. As the particles are being rolled along, current ripple marks are quite commonly produced. The process of their formation is identical with that of water-made ripple marks. Small eddies in the wind and variations in the size of the particles being moved cause the formation of alternating shallow depressions and low ridges (Figs. 280 and 212, page 199). The ripple marks advance

with the wind by the grains' being rolled up the gentle windward slopes of the small ridges and then rolling down the steeper leeward slopes into the depressions. In a stiff breeze ripple marks can easily be detected in motion.

Saltation.—In a strong wind a stationary or rolling particle may be continuously picked up from the ground and dropped, its advancement therefore taking place in a series of short jumps. This method of transportation is called "saltation" and considerable quantities of material are moved in this way, as saltation can be accomplished not only by a straight-moving wind but also and more especially by the numerous vertical and cross currents produced by irregularities of the land and the numerous objects upon it.

Suspension.—Whenever the velocity of the wind is sufficiently great, particles may be carried in suspension. The greater part of the sand grains so carried are transported within a few feet of the ground because the lower currents, being relatively slow currents (due to the numerous obstructions they encounter on the surface), are unable to lift the coarse sand particles to the higher currents that might be able to transport them.

Dust that is carried upward into the faster-moving wind above may be transported great distances. A strong wind blowing for two or three days in one direction in the semiarid southwestern part of the United States produces, as a result of transported dust, a haziness of the air and highly colored sunsets and sunrises in the adjacent windward regions. The dust particles that fall in the polar regions and upon vessels in mid-ocean were transported in the swift upper currents. The red rains (called "blood rains") of northern Italy furnish a very interesting example of long-distance transportation. Strong winds starting in the desert area of northern Africa, where they pick up the minute particles of hematite dust worn off of the sand grains of the desert, sweep across the Mediterranean; and, as they cross the Alps, their moisture is condensed to a rain that carries the red particles down upon northern Italy. The transportation of wind-blown dust is world wide. It has been said that every square mile of the land surface of the earth has received dust particles from every other square mile, a statement quite within the realm of probability, for dust particles are very small and readily transported.

Dust storms or sand storms are the moving days for immense quantities of material, but the wind is busy moving material in the intervals between storms, though it may be only a short distance.

Deposition.—In order to bring about deposition by the wind, all that is needed is to decrease its velocity until the sand or dust particles can no longer be moved. This decrease in velocity may be brought about by obstacles on the surface, such as fences, trees, and houses, or it

may take place because the force that set the wind in motion has ceased.

The first grains to be dropped or to cease being rolled would be the largest particles, of course, and so on down through the scale of sizes. Minute particles of dust, less than 1/2,500 inch in diameter, would continue to settle out of the air long after the wind had ceased blowing.

Common sites of deposition are small depressions and areas along fences and around bushes (Fig. 281), shrubs, trees, and larger objects if any are available. Forested areas as well as grass lands receive much fine wind-blown material, which soon becomes mixed with the local soil and loses its identity. Mountainous regions adjacent to deserts receive

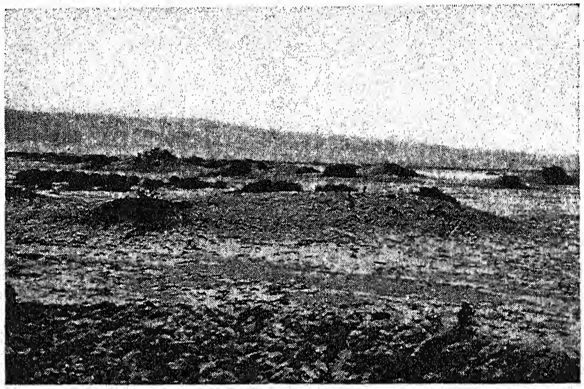


FIG. 281.—Sand deposited around sage-brush west of Lovelocks, Nevada. (*Photograph by W. A. Tarr.*)

large quantities of dust, though most of it soon finds its way into the streams unless the region is covered with forests. If an abundance of material is available, it is possible that deposition may start without the aid of an obstacle or a depression as a starting point.

Results of Wind Work

The results of wind work are twofold: *erosive* and *depositional.* On the whole the depositional features are the more common, but in certain areas the results of wind erosion are striking and abundant.

Erosive Features.—Wind transporting sand is a natural sandblast. Its effect on the land surface can be likened to the effect that would be produced by rubbing an immense sheet of sandpaper over that surface. Any object the sand moves over or against is abraded. Wind-worn surfaces are thus produced, and also other features due to abrasion.

Wind-worn Pebbles (Glyptoliths).—One of the striking results of wind action is the carving and shaping of pebbles, hence their name *glyptoliths*

(carved stones). The wind in driving sand against the side of a pebble carves and smooths it, developing a flat face, which, if the material composing the pebble is not of uniform hardness, is apt to be pitted (Fig.

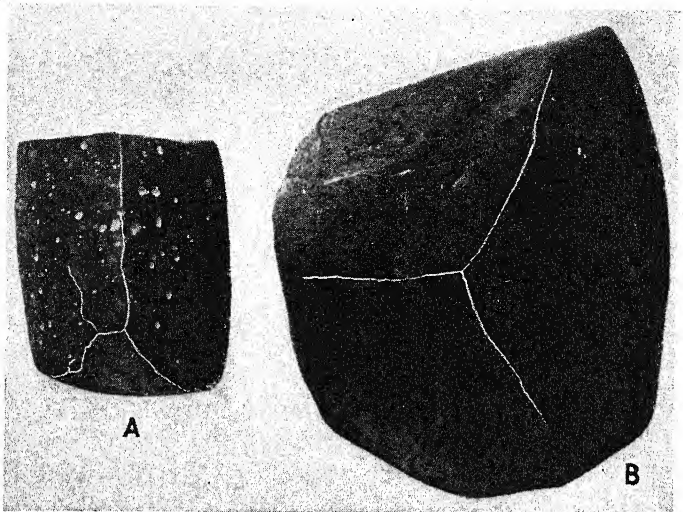


FIG. 282.—Wind-worn pebbles. (*A*) Pitted einkanter; (*B*) dreikanter.

282-A). If the wind varies in direction, faces may be developed on other sides of the pebble. Thus one, two, three, or more faces may develop. The faces are rarely of the same size or shape. When two of them intersect, a sharp edge is formed. If a single edge appears on the

FIG. 283.—Wind erosion in sandstone, southeastern Colorado. (*Photograph by W. A. Tarr.*)

sand-blasted pebble the latter is called an *einkanter* (a German word which means "one edge"). A pebble commonly has three faces, and thus three edges, and so is called a *dreikanter* (Fig. 282-B).

Rock Smoothing and Carving.—Abrasion by the wind produces smoothed rock surfaces. These surfaces, although very large, are also apt to be pitted. The pits range in size from minute irregularities of the surface to areas several feet across (Fig. 283).

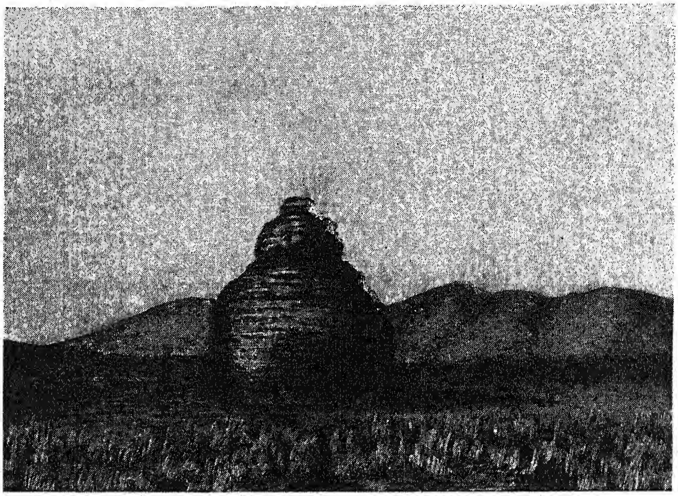


Fig. 284.—Jug-shaped hill formed by wind abrasion, southeastern Utah. Note absence of talus, which is removed as fast as formed. (*Photography by W. A. Tarr.*)

A surface known as *desert pavement* is a wind-smoothed surface of unusual character. It is produced on pebble-covered surfaces in desert regions. As the finer materials are carried away by the wind, the pebbles become packed tightly together, covering the entire surface. Then the

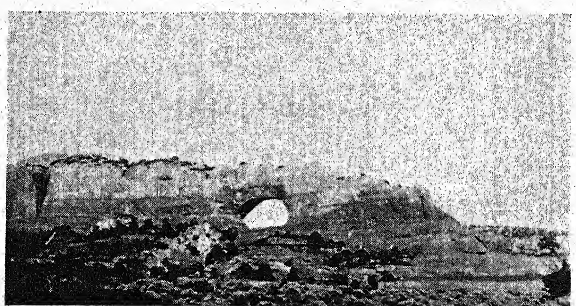


Fig. 285.—Natural bridge carved by wind in sandstone, south of Moab, Utah. (*Photograph by W. A. Tarr.*)

wind, sweeping its load of sand across this surface, wears the pebbles smooth. Since the pebbles consist of different kinds of rocks having various colors and shapes, the desert pavement is a natural mosaic.

If there are marked differences of hardness in the materials of a rock, various fantastic shapes may be produced by wind erosion. Thus the sand-blast of the wind, by cutting irregularly into the rocks, produces isolated, rounded hills, which usually have steep lower slopes because the greatest amount of cutting is near the bottom (Fig. 284). Talus slopes are absent in areas of much wind abrasion because of this great amount of cutting near the bottom of the slopes. The wind may also bore through a thin ridge or wall of rock and form a *natural bridge* (Fig. 285).

Depositional Features.—The material moved by the wind forms two dominant types of deposits, each of which owes its characteristics to the

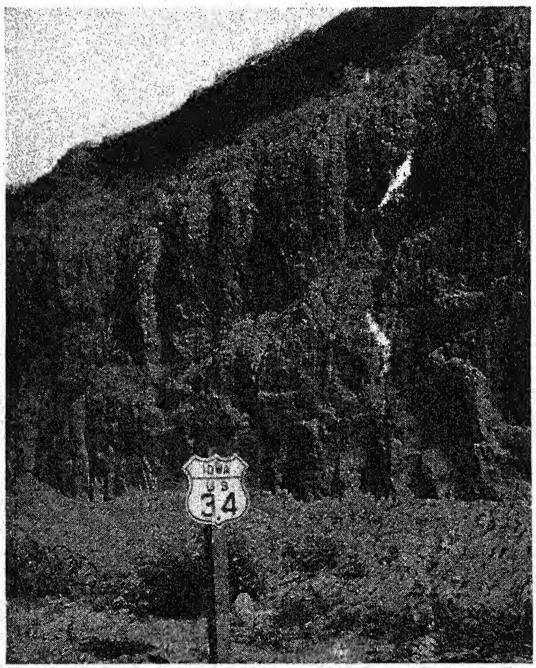


FIG. 286.—Typical vertical face of loess west of Red Oak, Iowa. (*Photograph by W. A. Tarr.*)

distinctive size of the materials composing it. Accumulations of dust and silt are called *loess* and accumulations of sand are called *dunes.* The two deposits are not usually closely associated.

Loess Deposits.—Loess consists dominantly (about 75 per cent) of quartz grains of silt size (0.1 millimeter or 0.004 inch) and clay. Very small amounts of the grains are larger than those of silt. Rarely, a few fresh-water or land snail shells are found in the material. The loess is usually buff to yellow in color and is remarkably porous. It possesses the property of standing with steep or vertical faces, as may be seen along highways built through loess (Fig. 286).

Loess is found on both sides of the Mississippi River from Louisiana and Mississippi north to Illinois and Iowa, along the Missouri River, and locally along other rivers in the central Mississippi Valley. It is found widely distributed in central Europe, and in Asia it occurs in Mongolia, Tibet, and China.

In the United States the loess deposits are thin, averaging between 10 and 20 feet in thickness and but rarely attaining a thickness of 50 to 100 feet. Those of Europe are also thin, but thicknesses of 300 feet are reported in China. Because of the softness of loess and the consequent ease with which it is excavated, great numbers of people in the loessial regions of China live in houses that are really caves dug in the loess. Loessial soils are wonderfully fertile and so are intensively cultivated wherever they occur.

As to origin it is now generally agreed that loess is due to wind action. The loess of America and Europe is found along rivers, where it is thickest near the river and thins out and disappears at a distance of 10, 20, or 50 miles. This distribution points to the river bed as the source of the material, as can scarcely be doubted by anyone who has watched the wind sweeping clouds of dust and silt up from the dried flood-plain of a river on to the bordering uplands. Most of the loess along these rivers was deposited during and following the glacial period, as all the rivers were then greatly overloaded with the fine material obtained from the melting ice. The loess of Asia apparently had its source in the deserts (such as the Gobi) of the central part of the continent. From these regions the wind carried the dust and silt to the south and southeast and deposited it in the greatest abundance in the province of Kansu. The Yellow River or Hwang Ho of China flows through this area and owes its color to the enormous amount of yellow loess it is transporting. Likewise the sea into which it drains (via the Gulf of Pohai) is known as the Yellow Sea.

Although essentially all loess deposits are composed of wind-blown material, the material of a few small deposits has the appearance of having been due to deposition in water, either in shallow lakes or on the flood-plains of streams.

Dunes.—Dunes are accumulations (mounds or hills) of sand. The term "sand" as used in this connection refers only to the size and not to the kind of materials present.

The *size of the particles* of most dune sand ranges in diameter from 0.05 millimeter or 0.002 inch (the smallest size in which the separate grains can be distinguished by the naked eye) to that of coarse gravel.

The dominant *shape of the grains* of dune sand is rounded (some are perfect spheres), but angular material also occurs. As noted above, rounded sand grains of quartz usually have a frosted surface.

The *composition* of most dune sand is dominantly *quartz,* though small quantities of any of the minerals forming or occurring in rocks may be present. Locally there are dunes that do not contain quartz as the dominant material. Dunes composed of *gypsum* sand occur in New

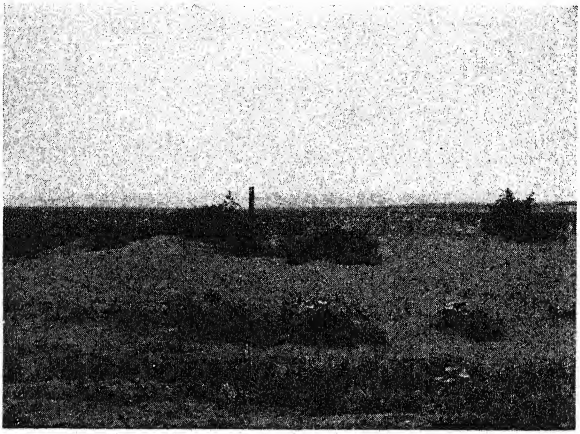


FIG. 287.—Clay dunes, northern Montana. (*Photograph by W. A. Tarr.*)

Mexico, others composed of *calcareous oolites* occur in the Bahamas and Bermudas, and low dunes of dried *clay* are found in Montana (Fig. 287). In order to make complete our list of materials that occur in dunes, we should include these composed of drifted *snow.*

FIG. 288.—Sand dunes in San Luis Valley, central Colorado.

Dunes are of all *sizes* (Fig. 288). They range from a few feet to 400 feet in height and from a few square feet to several square miles in area. In desert regions heights of 200 to 400 feet are common.

With a moderate wind and an abundant supply of sand the longer axis of a dune will be at right angles to the direction of the wind (Fig. 289-A), but a strong wind in the same area will develop dunes elongated parallel to the direction from which the wind is blowing (Fig. 289-B).

FIG. 289.—Sketches showing different types of sand dunes.

Less commonly, where the supply of sand is limited, *barchanes* or *crescent-shaped dunes* (Fig. 289-C) may form.

All sand dunes *migrate* to some degree, unless they become so covered with vegetation that the wind no longer has access to the sand. Migration is accomplished by the wind's blowing the sand up the gentle windward slope (*a*, Fig. 290) and allowing it to roll down the steeper (up to 33°) leeward slope (*b*, Fig. 290). As material is shifted from the windward to the leeward sides, the dune moves in that direction (shown by the dotted line in the figure). If the direction of the wind varies, the direction of dune movement varies with it. The rate of movement of dunes is slow, rarely exceeding 25 feet per year.

Migrating dunes may advance over forests, farms, houses, railroads, and highways, and may even bury villages and cities. The fact that dunes buried many cities of the ancient civilizations (Babylonian, Chaldean, and others) of southern Asia and thus prevented the complete destruction of the cultures of those periods has been a great aid to later generations of mankind in the work of unraveling the history of those civilizations.

If the migration of dunes is destroying valuable land, the movement may be stopped by planting over the surface grasses and shrubs that will grow in sand. This soon checks the movement of

the sand and thus the advancement of the dunes (Fig. 291). In many sandy areas of western United States the movement of the sand has been started when, the region having been opened up for settlement, the covering of grass and trees was removed in preparation for tilling the soil.

Sand dunes have a world-wide *distribution,* and although they are more numerous in arid regions they are also present in moist areas.

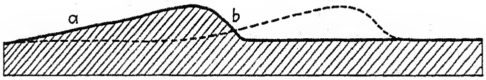


FIG. 290.—Sketch showing the movement of a sand dune.

Dunes are found along rivers throughout western United States, and also on uplands far from rivers if a source of sand, such as a sandstone, is available. From large sandstone areas in Oklahoma and Kansas, the wind has obtained sand with which it has built adjoining belts of dunes. Further downward cutting in these regions is now prevented by the fact that the sandstone contains so much salt and gypsum. These two

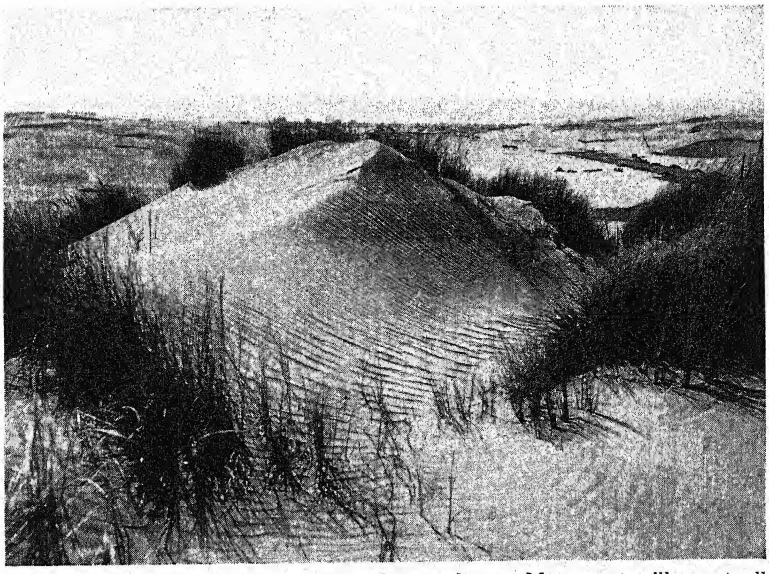


FIG. 291.—Vegetation getting a foothold on a dune. Movement will eventually be checked. Note current ripple marks on dune. Which way was the wind blowing that formed them?

minerals absorb and retain so much moisture that in rainy seasons the wind cannot blow the material away, and in dry seasons they form a crust which also prevents the wind from picking up the material. In this way the salt plains of these regions have been developed. Dunes are found along the sea shore and along lakes. Where there is an abundance of sand, dunes along the ocean have formed a belt many miles

wide. The dune belts along lakes (such as Lake Michigan) are narrower because, of course, the supply of sand is less.

Wind Placers.—As we have already seen, the work of the wind is not always destructive, and placers formed by the wind are another example of this. Since different minerals have different specific gravities, the removal by the wind of the lighter grains may bring about a concentration of the heavier minerals, and if any of the heavy minerals is economically valuable the accumulation or placer may be an important source of that mineral. Some of the gold placers of Western Australia (an arid region) were formed in this way by the wind.

Volcanic Dust Deposits.—Volcanic dust is carried long distances by the wind and forms deposits that are valuable as abrasive material because of the extreme fineness and sharpness of the particles. The volcanic dust deposits in north-central Kansas and southern Nebraska are examples.

CHAPTER XIII

STRUCTURES AND DIASTROPHISM

STRUCTURES

The size, shape, and arrangement of grains and crystals in rocks are called textures, and the larger features of all kinds are called structures. In recent years the study of structures has greatly increased in importance. Many structures are formed while the rock is being deposited or solidified and therefore are known as *original structures*. Others are later developments, brought about by heat, pressure, ground water, or combinations of these.

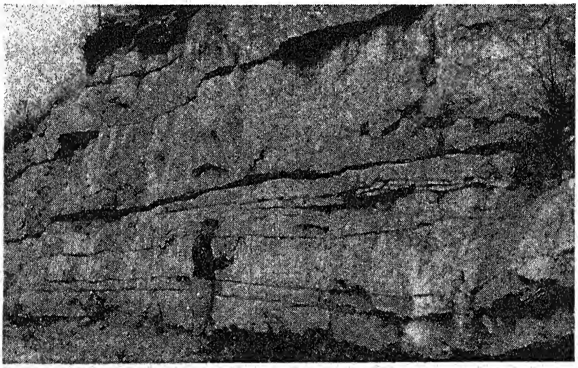


FIG. 292.—Thin beds and thick beds in the same section. (*Photograph by E. B. Branson.*)

Beds.—Some of the commonest structures are the beds of sedimentary rocks. Beds are original structures and are present in all rocks deposited by agents that sort the grains. Beds range from thinner than tissue paper up to more than 100 feet thick, but the more common range is from 2 or 3 inches up to 2 feet. Between beds are bedding planes marked by laminae made of materials different from the beds, or materials different in color or texture. In many quarries rock is taken out along the bedding planes, and such planes control the thickness of the quarried blocks. In fresh excavations bedding planes may be easily distinguished or they may be obscure. Weathering causes the materials along the bedding planes to appear different from those in the beds, and the bedding planes are likely to be evident as little reentrants in the rock.

Originally beds are nearly horizontal, as they are laid down in seas or lakes with nearly horizontal bottoms. The sea bottom in most places

slopes gradually from shore to great depths, but such slopes are too gentle to be detected by the naked eye.

Although sedimentary rocks are the only ones truly bedded, successive lava flows may appear bedded. Suppose that a thin lava flow covers a wide area and is followed by a period of erosion before another flow is spread out on top of the first. The two flows give the appearance of bedding that only close examination can distinguish from real bedding. Of course the student who breaks the rock and finds that it is igneous knows that the beds are not due to sorting and deposition.

Other Original Structures.—Among the original structures formed in or between the beds are concretions, nodules, geodes, cross-bedding,

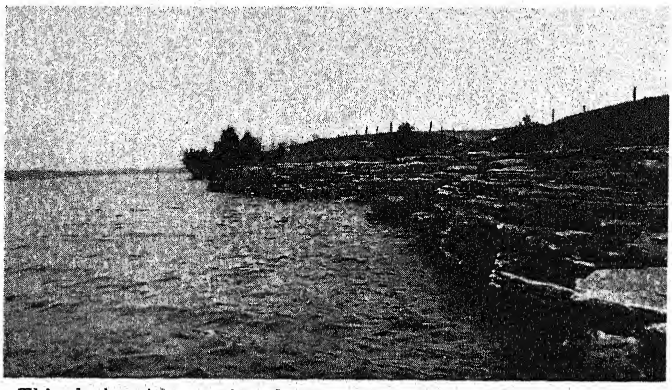


FIG. 293.—Thin beds with weathered reentrants, near Sacketts Harbor, New York. (*Photograph by Courtney Werner.*)

ripple marks, oolites, stylolites, and mud cracks, all of which are described in Chap. IX of this text.

Joints.—Cracks or joints are more common structures than bedding, as they affect all rocks. Most joints are nearly vertical and nearly all rocks have two sets, trending nearly at right angles. Some rocks are jointed so closely that it is difficult to obtain a piece more than 3 or 4 inches in diameter, and it is highly exceptional to find 100 feet of space between joints. An architect wishing to use pieces of rock 50 feet long is restricted in his choice of material, as jointing has limited the size of blocks. Most joints were formed during earth movements. There is no part of the earth that has not moved up or down many times during earth history. The movements were in most cases very slow, but they produced almost innumerable earthquakes, and the passage of the vibrations through the rock, repeated many times, created joints just as the progress of earthquake vibrations through a building makes cracks in it. It may seem doubtful or impossible that regions far from mountains[1] and far from any recent earthquakes have ever been affected by

[1] See New Madrid earthquake (p. 303).

great shocks, but even such regions as the Mississippi Valley have had serious earthquakes within historical times, and they actually created joints and enlarged those already present.

Near the surface joints may be closed or remain open. They may fill with weathered materials or may widen from solution. Joints can not extend into the zone of flow, some 12 miles below the earth's surface,

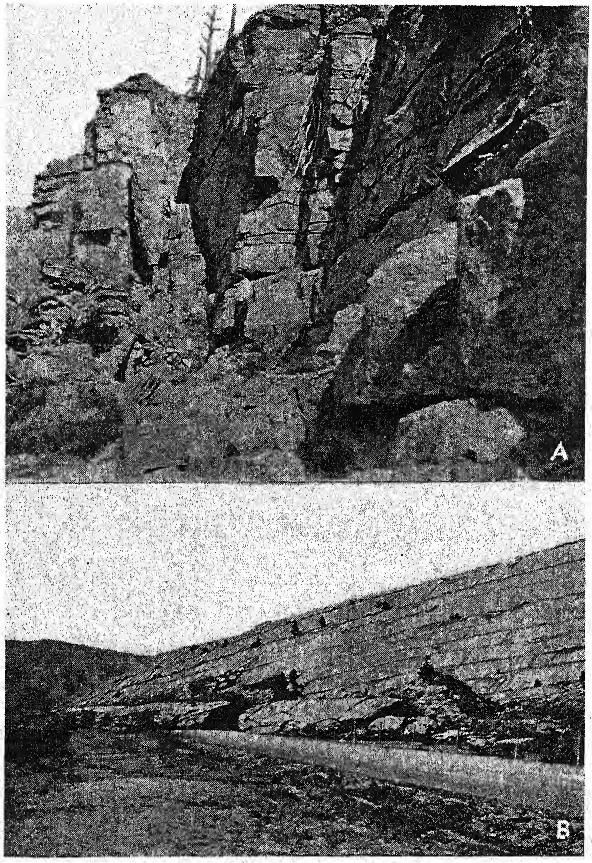


Fig. 294.—(*A*) Near view of joints in limestone near Lander, Wyoming. (*Photograph by E. B. Branson.*) (*B*) Surface of tilted sandstone showing joints, Muddy Gap, Wyoming. (*Photograph by Grace Carter.*)

as the rock is not strong enough to maintain cracks. Few joints have great vertical extent, and it is the joint group that reaches deep rather than a single joint. Below ground-water level they may fill with calcite, quartz, pyrite, and other materials deposited from solution. The filling of the joints with a mineral usually does not make the healed place as strong as it was before, and new earth movements are likely to break the rock along the old cracks.

Faults.—Along some of the cracks in the rocks differential movement takes place, *i.e.*, the rocks on one side of the crack move in a different direction or a different amount from those on the other. This is called faulting. Consider a north and south crack several miles long. On the west side of the crack the uplift is 1,000 feet, and on the east side 2,000 feet. The differential movement or *displacement* amounts to 1,000 feet. The same amount of displacement would have resulted if the west side had remained still and the east side had risen 1,000 feet, or if the east side had not moved and the west side had gone down 1,000 feet. Along

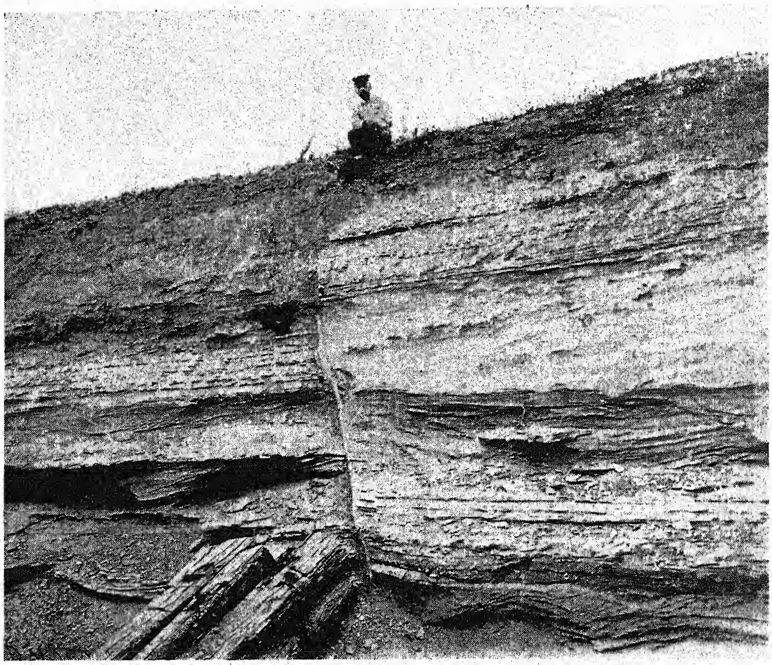


FIG. 295.—Fault showing displacement of about 3 feet. (*Photograph by Darton. Courtesy of U. S. Geol. Survey.*)

the crack mentioned above, the east side might have moved north while the west side moved south, or vice versa, giving rise to horizontal displacement. Horizontal movement occurred along the fault that caused the California earthquake of 1906, and railroads and fences that crossed the fault were offset the amount of the horizontal movement, in some places as much as 23 feet, although vertical displacement was less than 1 foot in most places.

Fault movements are likely to crumble and break rocks adjacent to the fissure. Just as a glacier moving over a surface plucks and scours, so the friction along the fault plucks, scours, and crushes. Along large faults the pressure of one wall against the other is almost inconceivably

great, and the downward pressure of a glacier 5,000 feet thick is very small compared to it. The movement of one rock surface against the other, even though the amount of movement is only a few inches, may smooth the surfaces until they are sleek as glass. Such surfaces are known as *slickensides* and are very common along faults.

Displacement.—The displacement, or the amount of differential slipping during faulting, ranges from a fraction of an inch to 15 miles or more. Displacements of 200 or 300 feet up to 2,000 or 3,000 feet are by no means uncommon in mountainous regions. The length of the fault line, *i.e.*, the length of the crack along which the movement takes place, varies even more than the amount of displacement. The fault that created the California earthquake of 1906 has been traced for nearly 300 miles. Faults a few inches long are not uncommon. The crack along

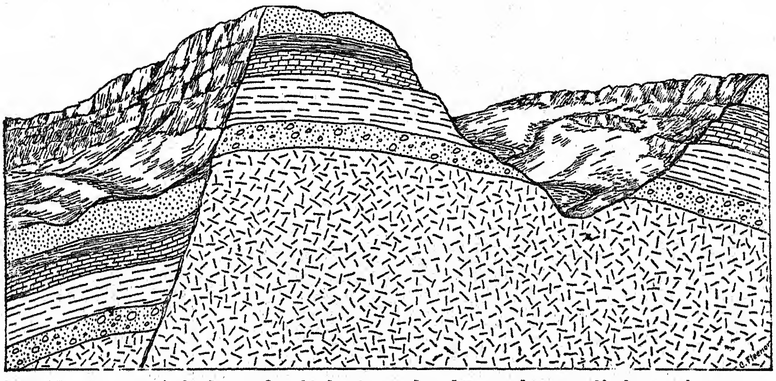


FIG. 296.—A fault, and a fault scarp that has undergone little erosion.

which movement takes place may range from vertical to horizontal, the more common direction being nearer to vertical. The fissures along which faults occur do not remain open in the deeper zones and are not likely to gap open near the surface.

Fault Scarps.—Where one side of a fault goes up relative to the other the displacement, if nearly vertical, may give rise to cliffs which are called fault scarps. The east side of the Sierra Nevada Mountains is a fault scarp several thousand feet high. This, however, is not vertical but has a slope of perhaps 20°. The west face of the Wasatch Mountains east of Salt Lake City contains the remnant of a great fault scarp. It too is not vertical but has a high dip. The question is often raised as to why most faults do not leave scarps. In the Appalachian Mountains there is a great number of large faults but rarely any fault scarps. The explanation may be that the fault is old and that erosion has reduced the high side to the same level as the low. In many cases the movement, even though large, took place so slowly that stream erosion reduced the high side as fast as it came up, and a fault scarp of any considerable size did

not form. Faults of 30 to 40 feet displacement, resulting in scarps of 30 to 40 feet, have formed during the present century and the results have been observed and recorded.

Many valleys have been formed by down-faulting of earth blocks between fissures that are roughly parallel. The Red Sea, Dead Sea, and some of the great lakes of Central Africa are in faulted valleys, sometimes called rifts. The basin of the Great Salt Lake in Utah is due partly to faulting.

Kinds of Faults.—The planes of some faults depart only a few degrees from horizontal, and in such cases the upper part may slide upward over the lower, bringing older rock on top of younger. The moving of the part above the fault plane upward over the part below could be brought about only by pressure from the sides, and such faults give positive indication of the direction of forces active in producing them. In low-

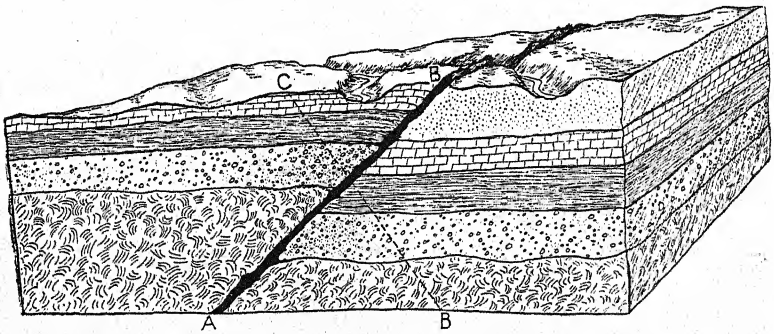


FIG. 297.—A mineral vein along a fault.

angle faults it is common to find that the edges of the overlying beds curve back (drag) toward the fault plane. In cases where the fault plane dips 45° or more the upper part usually slips down over the lower, and this movement must have been brought about by tension. Such faults are known as normal, as they are more numerous than the compression type, which is called reverse. Probably some faults extend nearly as deep as the zone of flow.

Ore Deposits along Faults.—The fissure along which faulting takes place and the crushed rock in that zone allow relatively free circulation of water, and if the water bears minerals in solution they may be deposited in this zone. Many of the rich ore deposits of the world were formed along faults. The broken and cracked rocks in the "drag" portion are favorable for water circulation and for the deposition of ore materials to a considerable distance from the fault itself.

Faults Lose Veins of Ore.—Although faults are favorable as places for deposition of ore, they may be troublesome in mining operations. Suppose that ore had been formed along a fault plane inclined at an angle of 45°. It might be discovered at the surface and shafts or core drill

holes sunk to find the direction, size, and nature of the vein beneath the ground. Sufficient ore having been proved, expensive machinery is installed and the mine put in operation. Five hundred feet down the vein stops abruptly against another kind of rock. The mining engineer knows that he has encountered another fault that has cut the vein; he

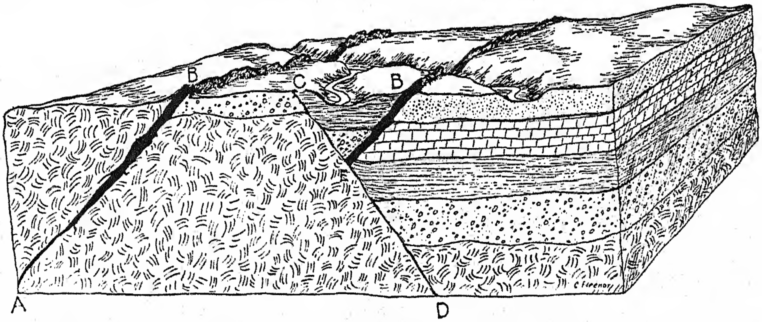


FIG. 298.—Another fault cut the one shown in Fig. 297 and offset the vein. If mining followed the vein from B downward, the vein would be lost at E.

must determine whether the vein has gone up or down and how far it has been shifted. It may have gone down so far as not to be reached profitably, or it may have gone up and have been eroded away. There are two ways to get at the problem: one, the expensive way of drilling to find the ore; the other, a geological investigation to see whether direction and amount of movement can be determined without the drill.

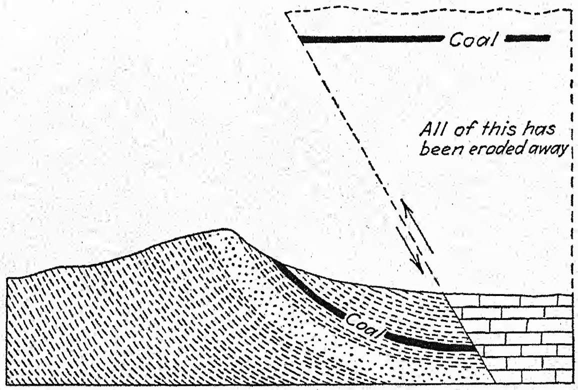


FIG. 299.—A coal bed lost by faulting and subsequent erosion. The part east of the fault went up 12,000 feet relative to that west of the fault, and all of the displaced part above the limestone has been removed by erosion.

A Fault Loses a Coal Bed.—Expensive prospecting where a small amount of geological investigation would have solved the problem was undertaken near the New River in Virginia. A coal bed dipping steeply eastward was being mined on the side of a mountain. Down-dip it was

found that the coal bed flattened out, and it was expected that the entire region to the east would be underlain by it at a workable depth. The coal was valuable, as it was high grade and the bed was about 5 feet thick. Companies leased all the land thought to be underlain by the coal and started sinking shafts and drilling to see at what depth the coal would be found. However, no coal was found at a distance greater than ½ mile from the mines. A geological examination of the region showed that a fault paralleling the mountains cut the vein about ½ mile from the mine and that the part to the east had gone up some 12,000 feet. As the surface to the east was at the same level as the surface on the west, there had been some 12,000 feet of erosion, and the coal had been carried away millions of years before mining was undertaken.

Faulted Oil Structures.—Not many years ago it was considered that a faulted oil structure was worthless because oil would have escaped along the fault, but it is now known that faulting in oil structures is usually favorable rather than unfavorable.

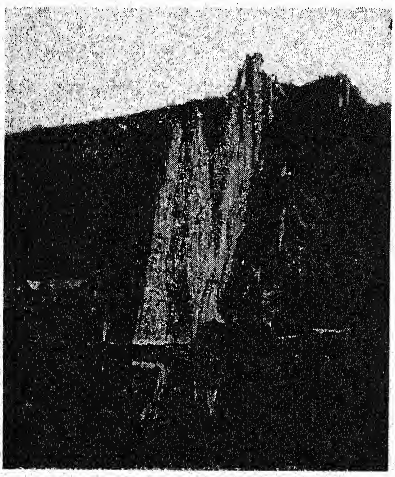


FIG. 300.—Vertical beds of limestone at Dinant, Meuse River, Belgium. (*Photograph by E. B. Branson.*)

Active Faults.—Faults along which movement has taken place within recent times are called *active.* When the Panama Canal was being planned extensive geological investigations were made to find whether any active faults existed in the Canal Zone. Two dangers were to be anticipated from active faults: first, earthquakes originate along faults, and shocks might do great damage to structures in the fault zone; second, a lock located on an active fault would be broken if movement occurred. A lock damaged by an earthquake might be repaired, but if located on an active fault it would eventually be ruined by fault movements.

One of the large cities in the United States had to take its entire water supply across an active fault. In this case provision was made for quick repairs in the event that the water mains should ever be broken.

Dips.—One who has learned that beds of sediments form in nearly horizontal position is likely to be surprised to find steeply inclined beds of limestone, sandstone, and shale, but such occur along nearly all mountain ranges and in some plains regions. The maximum amount of inclination of a bed from the horizontal is called the *dip;* vertical dips, though not common, occur in many places. Overturned beds, those tilted beyond the vertical, are nearly as numerous as vertical beds. Dips

ranging from a few feet per mile to 100 feet per mile are much commoner than greater dips.

Folds.—The beds in any region may dip in various directions. From a given place the dip may be in opposite directions like the roof of a house. This structure is called an *anticline, i.e.*, the beds are inclined away from

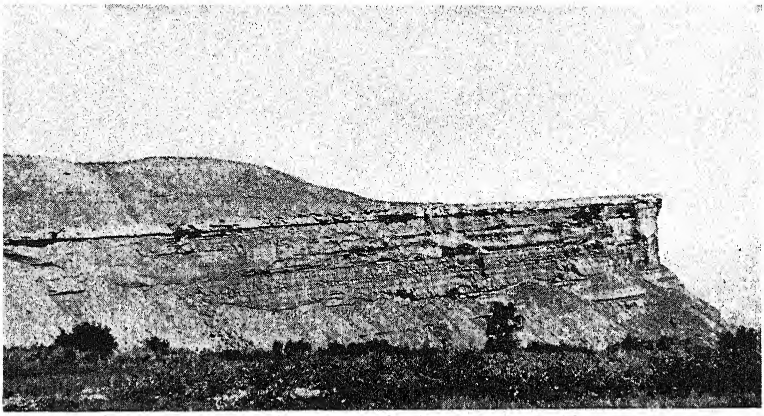


FIG. 301.—Beds dipping about 200 feet per mile. (*Photograph by Willis T. Lee. Courtesy of U. S. Geol. Survey.*)

each other. At another place in the same region the beds may be inclined toward one another so as to form a trough, called a *syncline*. One may have a mental picture of anticlines and synclines and go into the field expecting to find the anticlines forming hills and the synclines forming

FIG. 302.—Photograph of a small anticline and syncline. (*Photograph by W. A. Tarr.*)

valleys, but only rarely is that the case. These structures may not show in the topography owing to erosion. Erosion may have proceeded so far in places as to create synclinal hills and anticlinal valleys as shown in Fig. 308. In most cases the bend at the top of an anticline and the bottom of a syncline is not exposed. One finds beds dipping north and a

short distance away the same beds dipping south. Between the two places the beds must curve over at the top of an anticline, but the higher beds of the arch have been eroded away and many of the beds are concealed with mantle rock. Rarely, one finds the top of the fold clearly exposed as shown in Fig. 309. Rocks may dip in all directions away from a small area, making a structural dome or inverted basin; or they may dip in all directions toward a small area and make a synclinal basin. In many regions the rocks seem to be inclined in only one direction with no identifiable anticlines or synclines.

Anticlines were of interest to geologists chiefly as scientific phenomena until it was found that oil is trapped in some of them and that the main supply of oil comes from them. Anticline finding, mapping, and investi-

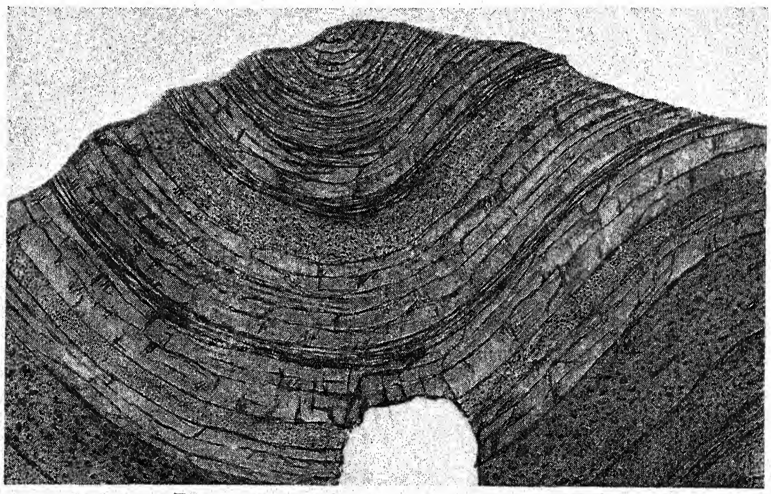


Fig. 303.—Tunnel driven through a syncline.

gating in various ways became a serious economic problem on which a great many geologists were employed. Only a small proportion of anticlines actually produce oil.

Folds as Engineering Hazards.—Folded strata must be seriously considered in various excavations and constructions. A tunnel was driven through a mountain in such a way that its top followed the bottom of a syncline. The engineer in charge relied upon the arch at the top of the tunnel to hold up the overlying rock, but the down-bending of the beds left inadequate support and the tunnel caved in.

Along one side of the Culebra cut in the Panama Canal the beds dip steeply toward the canal. A slippery shale bed slides on the underlying rocks when they are wet, and this has caused the slides into the Canal that have stopped traffic at some periods and have kept steam shovels at work removing the slides ever since the canal was dug.

In the anthracite coal region of Pennsylvania the rocks are greatly folded and much of the mining is in steeply dipping beds. The timbering of the mines is difficult and the mine roof is weak on account of the shattering of the rock when the folding took place. Waste rock is dumped back

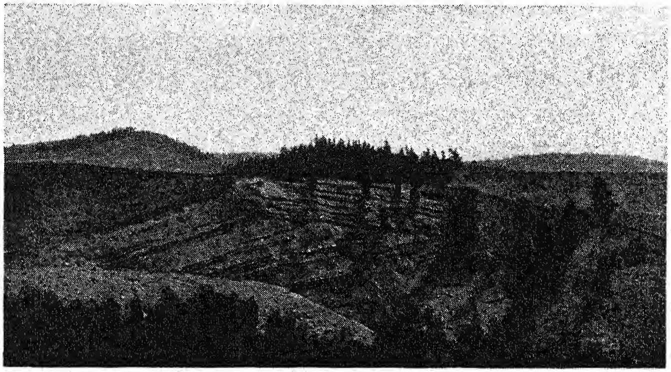


FIG. 304.—Unconformity between horizontal gray sandstone beds above and tilted red sandstone beds below. (*Photograph by E. B. Branson.*)

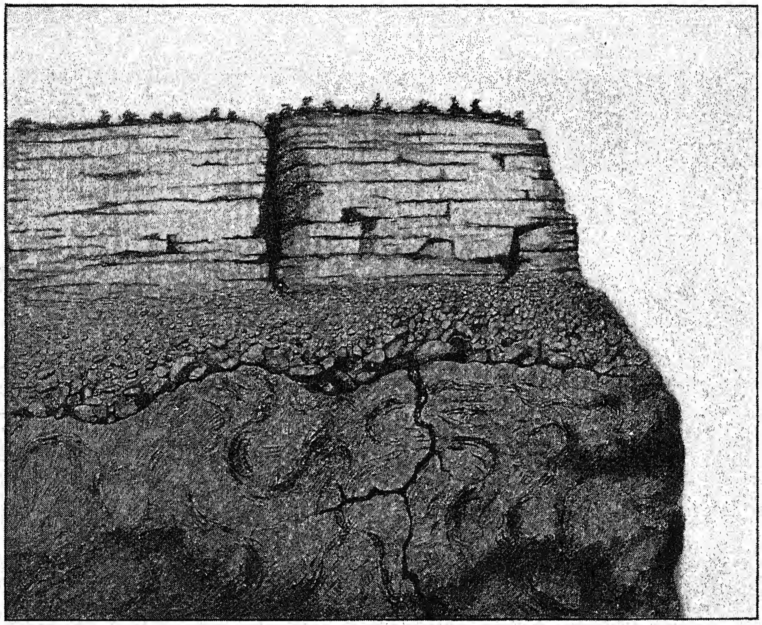


FIG. 305.—Unconformity with conglomerate resting on gneiss.

in the mines to fill up the excavations and aid in supporting the roof. Mining on steep slopes is expensive.

Unconformity.—After erosion of a land surface seas may advance over the eroded area and deposit beds of sediments on the rocks. The

relationship between the newly deposited sediments and the underlying rocks is called *unconformity*. Any agent—wind, glaciers, rivers, or organisms—might make the new deposits and the relationship would be unconformable. The essential of an unconformity is that an eroded surface mark the contact of the underlying and overlying rocks. The underlying rocks may be horizontal or dipping at any angle, or they may be igneous or metamorphic.

Unconformities are of great importance in geology as they record the conditions of the region during a time when sedimentary rocks were not forming at that place. They show that the area was land rather than sea and the geologist may be able to determine something of the length of time that the area was above the sea.

DIASTROPHISM

Many of the structures considered in the preceding part of this chapter were produced by earth movements. The larger earth movements, those which involve great masses of the earth, are known as diastrophism. In Chap. V the rate at which the lands are being reduced by stream erosion was found to be on the average about 1 foot in 5,000 years in the Mississippi Valley but the rate is 1 foot in 9,000 or 10,000 years in the entire North American continent. At that rate the North American continent would be cut to sea level in about 22,000,000 years. Allowing for decreased rate with lower grade of streams as base level is approached, it might take 50,000,000 to 60,000,000 years. Sixty million years is only a small fraction of geologic time, and in order to have kept lands available for erosion and for the continuity of land life there must have been some way of raising the lands in order to compensate for the down-cutting. Such land uplift has been observed in many places and evidences of uplift are almost universal. Two main types of diastrophic effects are recognized: general uplift without much differential movement, and local uplift. General uplift produces plains and plateaus, and local uplift may produce mountains. Downward movements seem to have dominated in the ocean basins and have been common on the continents.

Continental Movements.—The movements that produced plains and plateaus may be designated as continental. During some periods half of the lands of North America were under the sea and during other periods the continent, the part out of water, was 50 per cent larger than at present. At some times all of the lands were nearly base-leveled and at other times they were high. The lands of North America seem to be above average elevation at the present time. Continental movements are and have been so slow that they would not be noticed by residents of a changing region except by the change of shore lines, and inland that would not be evident. Ohio, Kentucky, Kansas, Montana—any region

without a coast line—may be rising, stationary, or sinking at the present time and the fact not be known.

The presence of sedimentary rocks containing fossils of sea animals is considered as conclusive evidence that the seas once covered an area, and the 75 per cent of the land area that is made up of such sedimentary rocks bears witness to the former great extent of the seas over the land. Unconformities between rock formations indicate times when the area was land and undergoing erosion. Over wide areas in North America lands more than 4,000 feet above sea level, made up of marine strata, indicate an uplift of more than 4,000 feet. On the other hand the presence of 40,000 feet of marine sedimentary rocks in places indicates a sinking of more than 40,000 feet to keep the region beneath the sea while the sediments were being deposited.

In places many unconformities are present and the land must have oscillated. It was above sea level and eroded, then sank below sea level and received sediments again, and these movements were repeated many times. Some areas, such as Illinois, Indiana, and Iowa, that are now far from the oceans alternated between land and sea during much of geologic history and were never affected by mountain-making movements. Only slight warpings occurred and left their records in slight dips of the rocks.

Mountain-making Movements.—Mountain-making movements consist of faulting and decided warping of the earth's crust. The areas affected are in some places hundreds of miles long, and within the area affected the rocks are strongly folded and in many cases faulted. The difference between the tops of the highest folds and the bottoms of the deepest troughs amounts to more than 50,000 feet in some mountains. Folded mountains seem to have been formed in the main by lateral pressure that forced the rocks to buckle up or break and fault.

Basins comparable in size to mountains and continents have been formed by diastrophism. The basin of Lake Superior is an example of differential down-warping and the Mediterranean Sea basin is an example on a much larger scale.

Causes of Diastrophism.—The causes of earth movements have been investigated by students approaching the subject from numerous points of view, but few consider that they have reached a satisfactory solution. It seems clear that sharp folds must have been caused by lateral pressure and that shrinking of the interior of the earth has been the source of the pressure. Shrinkage may have been caused by cooling, by pressure which caused rearrangement of molecules and atoms, possibly by atoms changing. Possibly all three have been instrumental in causing the shrinking, but their relative importance is not known.

Sediments may be deposited to such great thickness that their weight causes the sinking of the earth at that place. Such sinking would crowd

the underlying rocks and cause lateral pressure and up-warping of the margins of the sinking area.

Present Movements.—At the present time some lands are known to be rising slowly and others sinking. Northern Scandinavia seems to be rising at a rate of about 1 foot in 40 years. If erosion continues there at the average rate the land should be about 24,000 feet high in 1,000,000 years. The land would rise 25,000 feet and be cut down 1,000 feet. Part of the coast of south Greenland appears to be sinking. Stone huts built long ago by the inhabitants are now submerged, and the Greenlander has learned not to build his hut near the shore. Some old inhabitants of mountainous regions have thought that they were able to see fixed objects in the distance that were invisible from the same place during their youth on account of hills between. This would be evidence of warping down of intervening hills or rise of the land from which the observations were made or of the object seen in the distance. Such observations can not be trusted, as they depend on the memory of a person through a long period of years. On page 271 differential movement of several feet along fault planes is mentioned.

In Chap. VIII you studied drowned valleys as indicators of sinking coasts, and raised beaches, barriers, and other coast-line structures well above sea level as evidences of rising coasts.

Some igneous rocks crack while cooling and a close network of joints results, as explained on page 45. Such joints may range from horizontal to vertical. as they formed at right angles to the most rapidly cooling surface.

MOUNTAINS

The most striking features of the landscape are mountains, and more people are attracted to them than to any other land forms. A mountain is a hill with a relief above the surrounding land of 1,000 feet or more. Groups of mountains may have many peaks with small summit areas or may consist of ridges with few distinct peaks. On the basis of the ways in which they originated mountains are classified as volcanic, folded, circumerosional, and faulted.

Volcanic Mountains.—The simplest and in some ways most spectacular of all mountains are volcanoes. Volcanoes have always been a source of wonder and danger to man, and most of them are in volcanic mountains. Most volcanic mountains start with lava or other volcanic products issuing from an opening in level ground. Gradually the extruded material accumulates around the opening and may finally form a great mountain. If the extruded material is thin lava it spreads a long distance over the surrounding land and makes a mountain of wide extent, gentle slopes, and low elevation.

Kilauea.—Kilauea in the Hawaiian Islands is one of the best-known examples of lava cones of low slope. It covers an area of about 200 square miles and its slopes in most directions are so gentle that a car could be driven up without encountering a steep grade. At the top is the opening from which the lava flows. In considering that Kilauea has very gentle slopes for a mountain it should not be understood that there are no steep slopes. Stream erosion attacks volcanic mountains vigorously in regions of heavy rainfall, and in some places Kilauea is dissected by deep, steep-walled canyons; it is the original slope that is gentle, not one superimposed by some other agent.

FIG. 306.—Mt. Rainier, a volcanic mountain that has been greatly dissected by streams and glaciers. (*Courtesy of Rainier National Park Company.*)

Shape of Volcanic Mountains.—If the lava is thick the slope of the side is much steeper than when it is thin, and some lava cones are really steep. The lava mountain is actually made up of a succession of lava flows, some of which may be only a few inches thick and others hundreds of feet thick. The cone is symmetrical, although certain accidental things enter in to mar the symmetry.

Some volcanic mountains are made of ash and cinders, and they too are symmetrical. They may be very steep and, being composed of loose materials, erode rapidly. Lava flows are associated with ash and cinders and help to hold the shape of most of the ash mountains.

Well-known Volcanic Mountains.—In the United States volcanic mountains are few compared to other types; Mt. Lassen in California is the only one that has been active within historical times. Great areas

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in the United States are covered with extrusive igneous rocks, but in the main the lavas have come from fissure flows and have not formed mountains. East and north of the Rocky Mountains there is not a volcanic mound in the United States. The San Francisco Mountains in Arizona are lava cones not greatly dissected by stream erosion. Mt. Shasta and Mt. Lassen in California and Mt. Rainier and Mt. Hood in Oregon and Washington are well-known volcanic mountains. Mt. Vesuvius and Mt. Etna are among the best-known mountains in the world on account of their being active volcanoes. In Central America and South America many of the mountains are volcanic in origin, although most of the great mountains of South America are not of this type.

Mountains Caused by Folding.—The great mountain ranges of the world are in the main due to rock folding and subsequent erosion. Probably the Rocky Mountains are the best known of any mountains in North America, but most of those who have traveled widely among them scarcely realize what they are. They consist of a large number of inde-

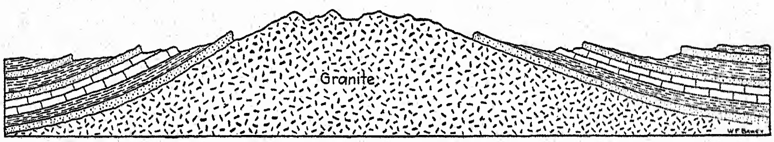

Fig. 307.—Mountains caused by folding and erosion. A sketch of the Big Horn Range.

pendent or semiindependent ranges, so numerous that no one is able to tell exactly how many and no map shows all of them. Nearly all of these ranges are the folded type.

The Big Horn Mountains, which trend north-south through central Wyoming, are a good example of folded mountains. They consist of one great fold, the highest part of which must once have been about 28,000 feet above sea level, and minor folds and faults on the sides. If this range had been shaped entirely by folding, its width, between flanks where the dipping rocks give way to nearly horizontal strata, would have been about 30 miles and its length about 150 miles. As soon as the central part reached a height great enough to cause water to flow from it stream erosion began cutting valleys into the fold. About 15,000 feet of sedimentary and igneous rocks have been cut away from the top and the elevation of the highest peaks is now about 13,000 feet. As the range consists of valleys and hills between the valleys, every hill directly and definitely related to a valley, the main features of the mountains are due almost entirely to stream erosion. Most of the valleys run almost at right angles to the main trend of the range and the streams have formed canyons that dissect the range from the middle to the margin on both sides. Two highways cross the range and both make use of canyons on both sides of the mountains.

When the folding of the range started, some 13,000 feet of sediments lay horizontally upon igneous and metamorphic rocks, and the folding raised the igneous and metamorphic rocks to the same extent as the sedimentaries. When 15,000 feet of rocks had been cut away from the top, the igneous and metamorphic rocks were laid bare in the middle of the range, and the flanks of the mountain were made up of dipping sandstones, shales, and limestones. The softer layers of rock were eroded away along the trend of the mountains and harder layers were left standing higher as ridges or hogbacks. The canyons running from the heart of the mountains outward are in igneous or metamorphic rock near the center of the range and cut through the sedimentaries on the flanks. However, the complexity of the range does not end with this, for in the later history all of the main valleys were glaciated and great numbers of cirques gave form to the highest peaks. The main valleys have been scoured out so as to be more or less U-shaped, and in the canyons of the higher parts of the range great numbers of lakes are present.

One might suppose that the Big Horn Range is of volcanic origin if he thought only of the igneous core, but the granites that constitute the interior of the range were intruded into other rocks long before the uplift of the range started. The lavas cooled and all of the rocks into which they were intruded were eroded away before the lowest of the 13,000 feet of sedimentary rocks were laid down. The range was forced up by great lateral pressure rather than by intrusion of lava into the core.

Most of the other ranges of the Rocky Mountains have had histories much like the one reported for the Big Horn Mountains. Most of them are made up of a core of igneous rocks with dipping sedimentary rocks on the sides. Stream erosion has laid bare the igneous rocks at the cores and created the ruggedness of the ranges, and in many of them glaciation has been superimposed on stream work. Only those ranges, however, that have an elevation of 11,000 or 12,000 feet or more above level have been glaciated; in all the rest stream erosion has been the sole shaping agent.

The Appalachian Mountains.—The Appalachian Mountains of eastern United States, although much lower and less picturesque than the Rockies, have had a longer and more varied history. They too are of the folded type, and the folding was much more intense than that described for the Big Horns. Instead of one large arch the Appalachians are made up of numerous smaller ones. In crossing the Big Horns one is impressed with the eastward dip of the rock on the east side and the westward dip on the west side, but in crossing the Appalachians one finds numerous changes in direction of dip and may cross many well-marked anticlines. These intense folds were not raised so high as the folds of the Big Horns and the greatest ones did not bring the igneous rocks high enough to be laid bare by erosion, so that most of the mountains consist

of ridges of sedimentary rocks. If there had been no erosion the Appalachians would have been a peculiar-looking compound ridge, like many sheets of paper compressed into hundreds of folds; but, as with the Rockies, erosion has been the agent that has created the mountains' forms. Erosion began as soon as folding brought the rocks above sea level and has removed more than 50,000 feet of strata from some places

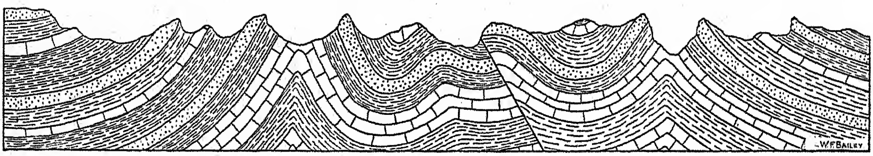

FIG. 308.—A section across part of the Appalachian Mountains.

and more than 20,000 feet from most places. One looks in vain in the mountains south of central Pennsylvania for any sign of glacial erosion. U-shaped valleys are not present. No cirques, no moraines, no glacial lakes appear. It is stream erosion that has shaped the topography. North of central Pennsylvania continental glaciers helped shape some of the lower hills and in places covered the entire range.

A striking feature of the Appalachian Mountains is the nearly level tops of the main ridges with their summits in the same plane. If no rocks

FIG. 309.—A domed mountain in west central Wyoming. The ridges are outcrops of hard rock about 200 feet high. The top of the dome has been removed by erosion. (*Photograph by Willard Bailey.*)

had been eroded from the ridges these would be explained as the original tops of the great folds, but thousands of feet of strata have been eroded from the top of every ridge. It does not seem possible that independent stream erosion could produce level-topped ridges of about the same elevation. If all of the valleys between the high ridges were filled to the tops of the ridges a nearly level plain would result. There are only two

ways in which such plains could be produced: one by the filling of a depression with sediments, which would make a plain of nearly horizontal layers, and the other by stream erosion carried to peneplanation. The latter explanation fits the case and we conclude that the entire region was

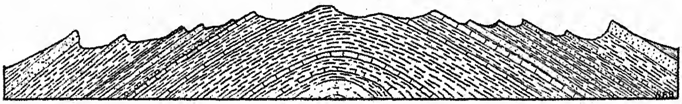

FIG. 310.—A section of the domed mountain shown in Fig. 309.

reduced nearly to a peneplain. This erosion surface later was raised and much dissected by streams, and the tops of the ridges are the only places that are still in the old plain. There are other evidences that the old Appalachian folds were peneplaned after their original great uplift, some of

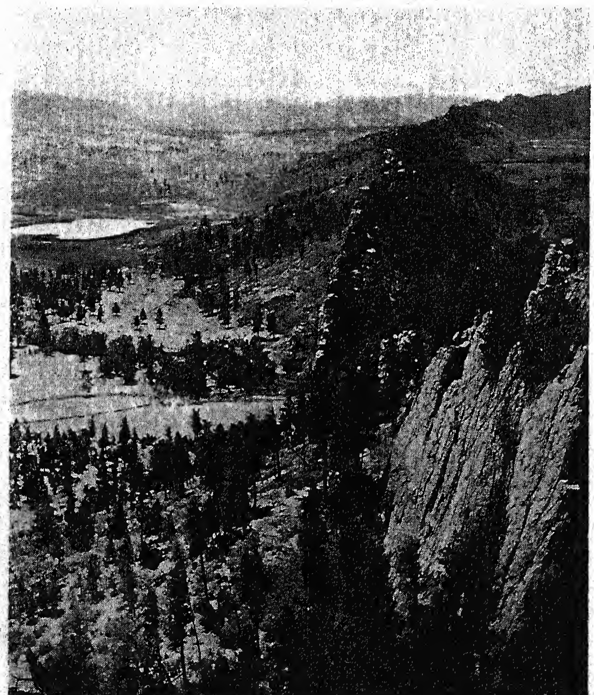

FIG. 311.—A hogback mountain in western New Mexico. (*Photograph by Willis T. Lee. Courtesy of U. S. Geol. Survey.*)

which will be given in the summary of the history of the Appalachian Mountains. The southeastern part of the Appalachian Mountains is composed mainly of metamorphic rocks and the general appearance of the region is not of parallel ridges, like those in the region made up of sedimentary rocks, but of dendritic valleys and ridges.

Although the Appalachians are an intensely folded range the Alps are much more complexly folded, and beginning with the Big Horns form

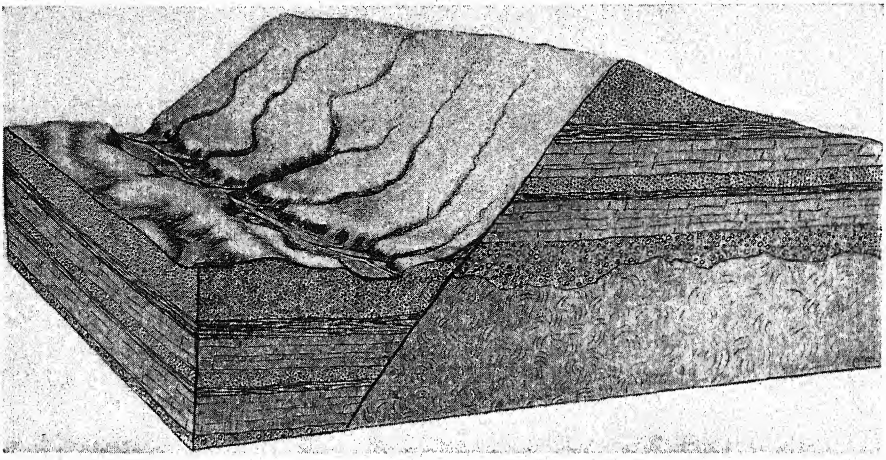

FIG. 312.—A mountain caused by faulting. One face of the mountain is a slightly dissected fault scarp. The displacement was about 1,500 feet.

a series: a huge simple fold; Appalachians, many sharp folds; Alps, many more folds than the Appalachians, overturned folds, and complex faults.

Hogback mountains are ridges or series of ridges caused by erosion of dipping strata. The softer beds are cut much lower than the hard and

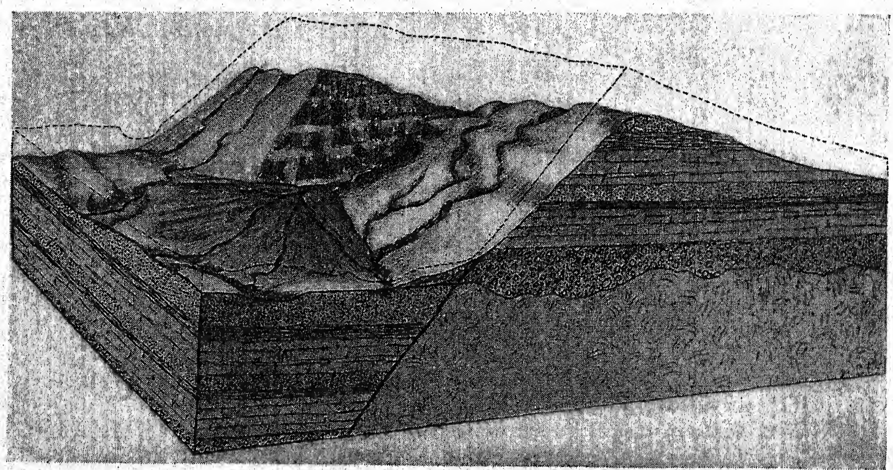

FIG. 313.—The mountain shown in Fig. 312 after it had been greatly eroded. None of the original fault scarp indicated by the dotted lines, remains.

the hard form one slope of the ridges. Such mountains form in regions where the beds have been tilted in one direction and eroded as shown in Fig. 111, but hogback mountains isolated from others are rare. The

Great Hogback in western Colorado is one of the best known of this type in North America. Figure 311 is of a hogback mountain in northwestern New Mexico. Most of the ridges of the Appalachian system are hogbacks, and most of the chains of the Rocky Mountains are flanked by hogbacks.

Mountains Caused by Faulting.—As stated in a previous paragraph some fault scarps are high and steep and form the sides of mountains. The ruggedest mountains in the interior of the United States are the Tetons of western Wyoming. The east face of these mountains was once a fault scarp. Erosion has destroyed the scarp but has left the moun-

Fig. 314.—Rugged mountain features in Alaska produced by streams, glaciers, and weathering. (*Official photograph, U. S. Navy Air Corps.*)

tain peaks steep on the faulted side. Some mountains are uplifted blocks with faults on two or even four sides. Many of the Great Basin ranges of the United States are tilted fault blocks. As with most mountains the main topographic features of mountains caused by faulting are erosional, and the older the range the less conspicuous the fault scarps.

Most mountains are faulted to some extent. Some parts of the Appalachians are cut by many faults with thousands of feet of displacement while other parts are almost fault-free. Great folds may contain faults parallel to them or across them.

Mountains of Circumerosion.—Many low mountains are remnants of horizontal strata that have been left by stream erosion. Where valleys are deep, like the Colorado and its tributaries in northern Arizona, the region becomes mountains when it reaches a mature stage of topography. The top of the Mesa Verde in southwestern Colorado has an area of several thousand square miles. Its sides are very steep owing to the top being made of a resistant sandstone several hundred feet thick which rests on shales some 2,000 feet thick (see Fig. 104). Streams have cut

deeply into the shales and removed all of the sandstone over a large region on all sides of the Mesa, leaving it a steep-sided, flat-topped mountain

FIG. 315.—Mountain features in Yosemite National Park produced by streams and glaciers. (*Official photograph, U. S. Army Air Corps.*)

some 2,000 feet high, flanked by lower hills made of shales. (Figure 117 was photographed from the hill shown in Fig. 106, a butte isolated from

FIG. 316.—Mountains of circumerosion near the Grand Canyon of the Colorado.

the Mesa.) Some parts of the Mesa were dissected by stream erosion, leaving many buttes. Both mesas and buttes may be mountains if their relief is 1,000 feet or more.

The Catskills in eastern New York are mountains of circumerosion carved in nearly horizontal strata. Grand Mesa in western Colorado, another mountain of this class, has a relief of more than 3,000 feet. If one could imagine the region of the Grand Canyon of the Colorado dissected by tributaries 50 miles long, as deep as the Canyon itself, he would get a picture of mountains of circumerosion rising to heights of a mile or more and covering a great area.

CHAPTER XIV

EARTHQUAKES

In preceding chapters we have shown that numerous physical forces are continually at work within the body of the earth and upon its surface. Those agents working on the surface are constantly changing the shape and size of the features that give it variety and beauty. Likewise the physical forces beneath the surface are rearranging rock materials by shifting magmas about and altering the structure of solid rocks. The adjustments beneath the surface, however, involve various crustal movements, one of which because of its suddenness and intensity is known as an *earthquake.*

No demonstration of the mighty forces at work within the earth's body is so appalling to man as are earthquakes. They occur suddenly and swiftly, involve vast areas, and leave a trail of destruction behind them. Mountain making is an evidence of the tremendous forces that act upon portions of the earth's crust, but the growth of mountains is so slow that the span of man's life is much too short to enable him to detect the movements that take place. It is very different, however, with earthquakes. The solid land shakes like the leaves on an aspen tree, surface objects are injured or destroyed—and all in the space of a few seconds.

Volcanoes have been looked upon with awe and terror ever since primitive man's first encounter with their fiery floods, and within the historical period of the human race the toll of life taken during volcanic eruptions has amounted to many thousands. The destructiveness of volcanoes, however, does not compare with that of earthquakes, for usually there are signs of an approaching volcanic eruption and thus the inhabitants of nearby regions are able to escape. Earthquakes come without warning. Furthermore, volcanic areas are fewer and more sparsely inhabited than are the areas subject to earthquakes, and in the earthquake regions the shocks are just as apt to occur, of course, in the most densely populated areas, where their destruction of life and property is enormous, as in the regions of scattered population. Recent earthquakes in congested areas have been in Japan, in Messina, Italy, and in San Francisco and Long Beach, California.

Science has as yet failed to safeguard man against earthquakes by devising a method of detecting them in advance. The late Dr. F. Omori, director of the Tokyo Seismic Observatory and one of the foremost authorities on earthquakes, predicted, in 1921, that within six years

of that date a destructive earthquake would occur in Japan. Actually it came within two years; but, in view of the fact that an earthquake may come and go in two minutes, any prediction in terms of years is of little value as a warning. Seismologists (students of earthquakes), however, are eagerly striving to invent instruments or devise methods by which warnings of an approaching earthquake may be given. One such instrument that is now being tried measures the gradual tilting of the ground that occurs before a severe shock. A tilt of $1/30$ inch in a mile can now be detected, which may prove helpful in making adequate warnings a possibility. So rapid are earthquake movements that no means of communication yet devised by man is swift enough to enable those near the center of a disturbed area to warn the inhabitants of surrounding areas in time for them to escape.

Recorded descriptions of earthquakes go back nearly 2,500 years. Herodotus, Pliny, Livy, and many other historians mention their occurrence and destructiveness; hence man has long been accustomed to pay human toll to the earthquake. Much superstition has surrounded their occurrence; it was thought that they were imposed as a punishment for the misdeeds of the people living in the affected area.

An earnest effort to study the character of the movements, speed, source, and cause of earthquakes began about 1840. Though much has been learned in the 94 years of study, the appalling destructive power of the earthquake over man and his works is as great as ever. In fact this power is greater than it was formerly, for man has aggregated millions of his kind into small areas, has housed himself in death traps, and thus has paved the way for nature's demonstration of the fact that she brooks no control of her forces by her own progeny. Man must work in conformity with nature's laws, for only by so doing can he hope to avoid paying the extreme penalty. The occurrence and force of earthquakes should prove of benefit in correcting the arrogance of man by showing him his own puniness and weakness and also in developing in him a fuller appreciation of nature's laws.

Earth movements may be fairly well classified in two groups: the small but rapid movements, and the great, slow movements. It is the rapid movements of earth masses that are called "earthquakes." These movements may be so small as to be barely capable of detection by the most delicate instruments, or they may be of such magnitude as to be noticeable to all at distances of several thousand miles. An earthquake is in reality a vibration of a rock mass that moves forward and then returns to essentially its former position. The total movement (save at the point where it originates) is small.

Methods of Detecting and Recording Earthquakes.—The science of determining the size and character of earthquakes is called *seismometry* (*seismos* = "earthquake"; *metron* = "measure"). The first instru-

ments made were able to record only the fact that there had been an earthquake, and so furnished no information as to its size or velocity. Such instruments are called *seismoscopes*. The first one was invented in A.D. 136 by a Chinese. Many curious devices have been invented since that time. Anyone can easily make a simple seismoscope by placing a small round rod of wood or metal in a vertical position on a horizontal plane that is covered with fine sand to keep the rod from rolling. A moderate earthquake shock will upset this rod, and it will fall in the direction the earthquake is moving.

The detailed record of an earthquake is made on an instrument called a *seismograph*, which was invented and first used in Italy about 1841. The fundamental requirement of a seismograph (Fig. 317) is that it have

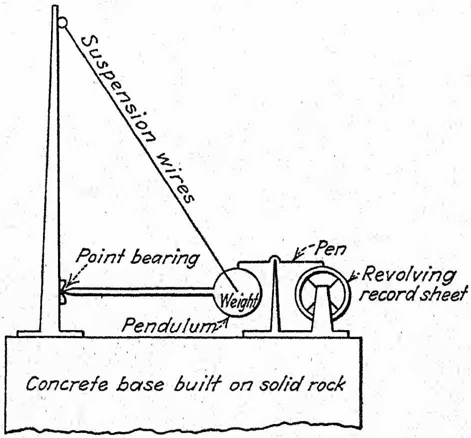

FIG. 317.—Diagram of a horizontal seismograph.

a delicately mounted heavy pendulum that remains essentially stationary as the earth moves beneath it. A long, slender rod rigidly attached to the pendulum supports a self-feeding pen which rests upon a surface of smoked paper—the record sheet. During an earthquake shock the pendulum and the pen are stationary while the record sheet moves with the earth. The pen thus registers the movement on the paper; and, as the record sheet is wound on a drum run by clockwork, the exact time of the movement is also recorded. In the latest models of seismographs the record of the vibrations is photographed and thus the friction of a pen is eliminated. The pendulum may be suspended vertically, horizontally (Fig. 317), or it may be inverted and rest upon a pivot. Some inverted pendulums weigh many tons.

An earthquake may involve movement in three directions: one vertical (usually small compared to the other two) and two horizontal. Most modern instruments record the horizontal movements in a north and south and an east and west direction. The record of an earthquake

shock is called a *seismogram* (Fig. 318*B*), which is really the earth's autograph of its movements. The records show that the movements during an earthquake are very complex. The instruments are very sensitive, recording minute shocks. Strong winds, the firing of cannon, or the passing of loaded trucks all leave a record on the sheet.

Velocity of Earthquake Waves.—A study of seismograms has shown that there are three types of earthquake waves. Two of the waves take

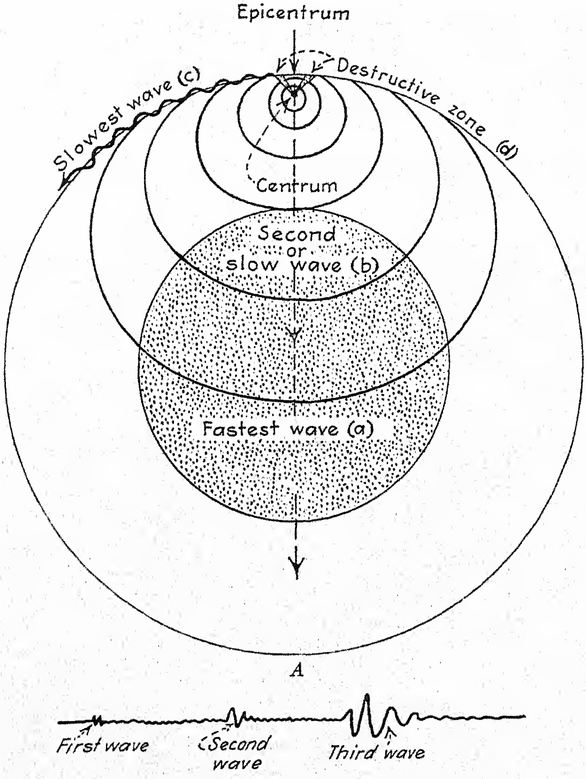

FIG. 318.—(*A*) Cross section of earth showing centrum and epicentrum of an earthquake, also course of waves produced by the earthquake and the most destructive zone (*d*) about it. (*B*) Ideal seismogram. (*Modified after N. H. Heck, Scientific Monthly,* 1930.)

a short course through the earth and the other one goes around the surface. The first wave (*a*, Fig. 318 *A*) passing through the earth is much faster than the second one (*b*, Fig. 318 *A*). The wave that goes around the outside (*c*, Fig. 318 *A*), though the slowest of all, is large and consequently does much damage. The relative size of the three waves is indicated in the seismogram at *B* in the figure.

The first of the waves (*a* and *b*, Fig. 318) to reach an instrument are those that take the shorter route through the earth. These are the

preliminary tremors. Some of these waves travel as fast as 6.75 miles per second (375 miles per minute). They could thus traverse the diameter of the earth in 20 minutes. The determination of the velocity of these waves has added much to our knowledge of the condition of the interior of the earth, which has been shown to be 1.5 times as rigid as steel. It is the study of the paths of these waves that has revealed the presence at the center of the earth of a core (stippled area, Fig. 318) composed dominantly of metals (iron, nickel, and many others). The radius of this core is about 3,400 kilometers (2,110 miles) and waves passing through this portion of the earth travel faster than through the outer portions.

The velocity of the slow surface wave rarely exceeds 2 miles per second (120 miles per minute) and may be only 8 or 9 miles per minute. This great reduction in velocity is due to the great abundance of cracks and fissures in the rocks of the outer part of the earth.

Amplitude of Earthquake Waves.—The actual distance that the ground moves, known as *the amplitude of the vibration*, is always small. A movement of 3/4 inch will destroy a city; a movement of 3/8 inch is a severe quake; and one involving only 3/16 inch will shatter a chimney. Rarely, the amplitude of waves is larger. In the Japan earthquake of 1923, the amplitude of the wave that caused the greatest destruction was 3.5 inches. One of the later shocks had an amplitude of 7.1 inches, but it was less destructive because of a much slower velocity. Very probably there have been earthquakes of larger movements which our seismographs were unable to record.

Time Length of Earthquake Shocks.—An earthquake rarely lasts more than 2 minutes and most of them only a few seconds. The California earthquake of 1906 was of less than a minute's duration, and the earthquake at Assam, India, in 1897, lasted 15 seconds. Messina, Italy, was destroyed in 35 seconds.

Intensity of Shocks.—An earthquake originates at a point or along a line usually called the *centrum* (Fig. 318). On the surface over the centrum is a point called the *epicentrum*, from which the intensity of the

Scale of Earthquake Intensity

Intensity	Description
1	Earthquake detectable only by instruments.
2	Very feeble.
3	Feeble.
4	Noticeable by man, but no damage.
5	Felt generally.
6	Slight damage.
7	Walls cracked.
8	Badly built houses destroyed.
9	Violent; much destruction and loss of life.
10	Catastrophic.

shock decreases with the distance. Scales showing the variations in intensity have been devised and are generally used in describing the character of the shock. A scale recently (in 1930) suggested by McAdie is given at the bottom of the opposite page. This scale is a convenient means of comparing shocks of different areas and also those of different parts of the same area.

Frequency of Shocks.—Earthquakes are occurring all the time. The estimate has been made that one occurs in some part of the earth every 2 hours and 27 minutes. Certain areas undergo a vast number of shocks of varying intensities. Japan and Italy are each credited with about 1,500 shocks a year, which is an average of nearly 4 per day. The

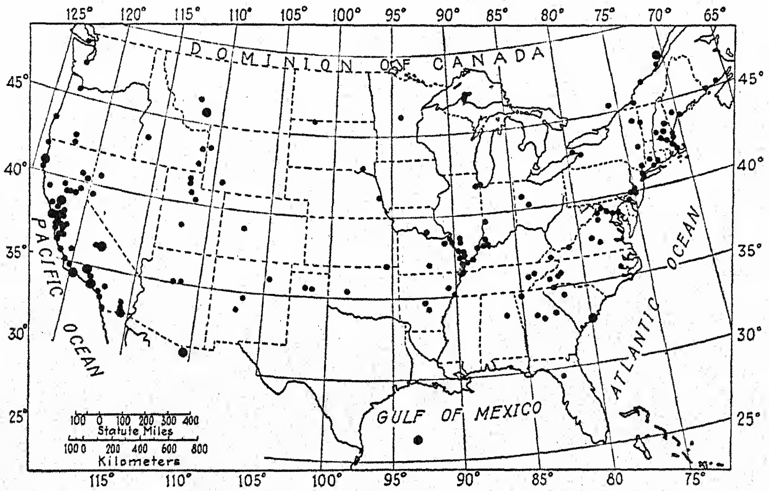

Fig. 319.—Map showing location of earthquakes in the United States. (*After N. H. Heck, Scientific Monthly*, 1930.)

records from 1875 to 1925 show a total of 27,500 shocks for each of these two countries. Other countries have had hundreds or thousands of shocks during the last 50 years. California has about 200 shocks of varying intensities per year. During a period of 3 months in the early part of the nineteenth century there were 1,874 shocks in the New Madrid area in southeastern Missouri and western Tennessee, but only 8 of them were severe.

Earthquake Zones.—Earthquakes occur most abundantly in areas containing mountains (especially the younger mountain ranges), which shows that the stresses set up in the rocks during the formation of the mountains were not all relieved but are still causing movements. Though earthquakes occur in regions of older mountains, such as the Appalachians, the stresses in such regions have been largely relieved during the long interval since the folding took place. The margins of the continents are also weak zones and hence are the locations of many earthquakes. It is

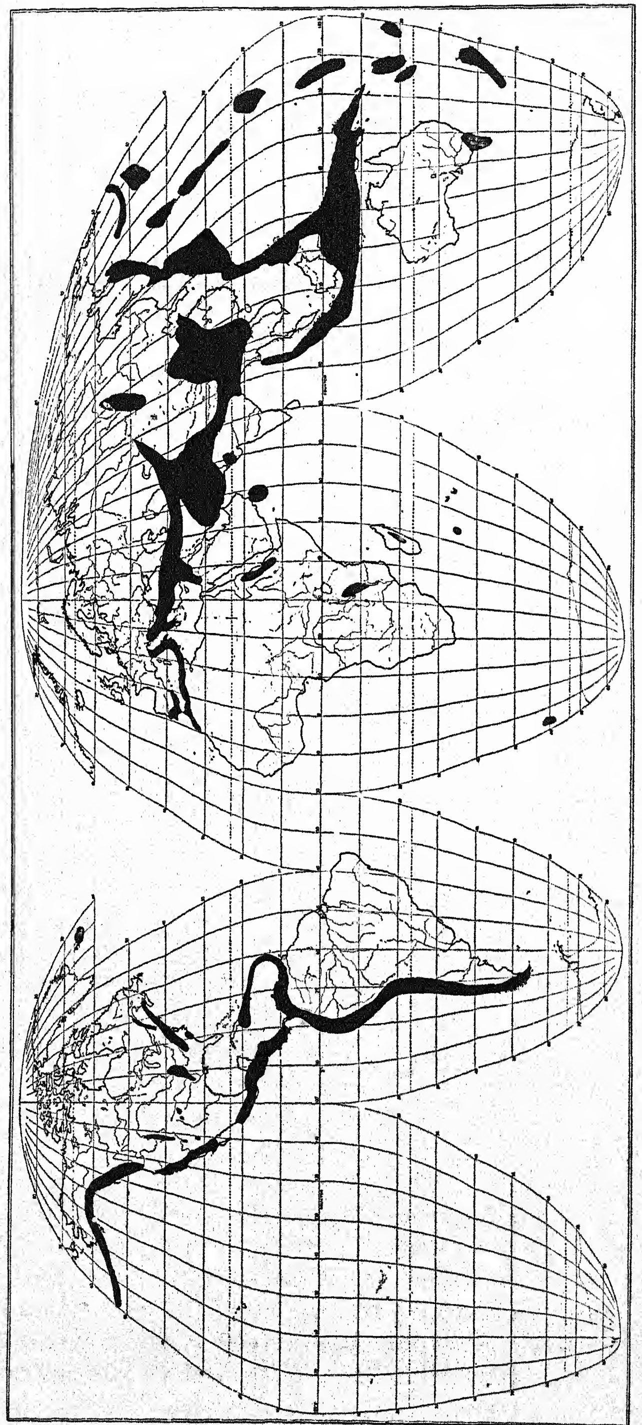

FIG. 320.—Map of world showing distribution of earthquake areas. (*Based on No. 101 Hc of the Goode Series of Base Maps. By permission of the University of Chicago Press.*)

worth noting that about 53 per cent of all earthquakes occur along a belt of younger mountain ranges (the Alps-Caucasus-Himalaya belt), and 41 per cent along the margins of the continents around the Pacific Ocean. The other 6 per cent are scattered over the earth. Figures 319 and 320 show the location of the earthquakes known to have occurred in the United States and the world, respectively.

Causes of Earthquakes.—Earthquakes originate from various causes. These are, in the order of their importance: *faulting, volcanism, landslides,* and the *collapse of cavern roofs.* The last two causes are local in extent and relatively unimportant, so will not be discussed here. The vast majority of earthquakes originate within 10 miles of the surface, though some may be due to causes acting at much greater depths.

Earthquake Waves Due to Faulting.—Most earthquakes are directly associated with earth movements along faults. It is this movement associated with faulting which sets up the elastic waves that produce an

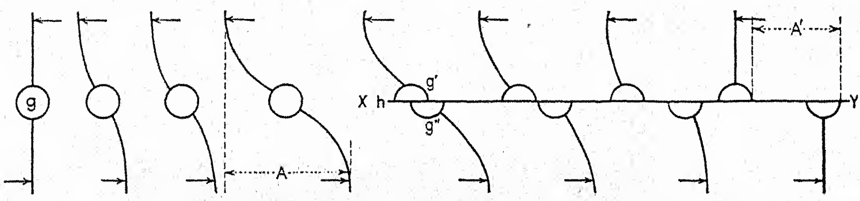

FIG. 321.—Diagram illustrating the stresses that produce a fault.

earthquake. An examination of Fig. 321 will help to make clear just what happens along a fault plane when movement occurs. A slow differential pull exists within the rock, the direction of which is shown by the two sets of arrows. As a result of this pull, a strain develops in the particle g, tending to separate it into two parts g' and g''. If the strain gradually increases over a long period of time, the pull on both parts of the particle will increase until finally it amounts to that indicated by the distance at A. If the pull or strain exceeds this distance, the particle will separate, as has occurred at h. The earthquake shock starts the instant the rupture occurs. The parts g' and g'' continue to move apart along the plane xy (the time required for the separation is measured in fractions of a second), and finally come to rest separated by the distance at A', which is probably less than that at A. The sudden parting (called the *recoil*) and attendant moving of the particle (and, of course, those adjacent to it) start the waves that form the earthquake. The process can be illustrated by slowly stretching a rubber band until it breaks. The elastic property of the rubber causes the two parts of the band to snap back, just as the elastic property of the rocks causes the rebound following their break. Rocks are remarkably elastic within narrow limits.

The amount of movement along a fault plane is influenced by many factors, the chief of which is the quantity of strain that had accumulated in the rocks. It depends also on the character of the fault plane, *i.e.*, whether it is an old or a new one. The amount of slipping accompanying the movement thus varies widely. The slipping during the California earthquake of 1906 was dominantly horizontal and amounted to 23 feet. The vertical slipping during an earthquake at Yakutat Bay, Alaska, in 1899, amounted to 48 feet; and in New Zealand, in 1929, to 20 feet. In numerous minor shocks, however, the slipping is no more than a few inches (Figs. 322 and 323).

After an earthquake has occurred, the rocks adjacent to the fault undergo adjustment for a considerable period of time. This causes a

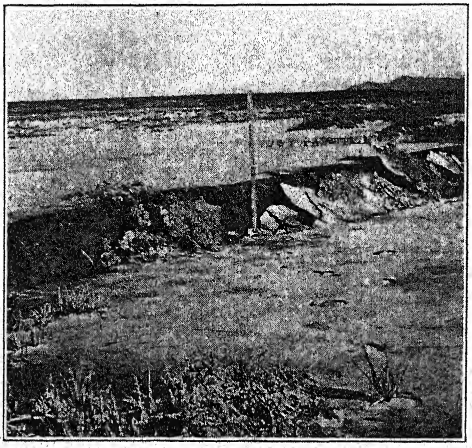

FIG. 322.—Fourteen-inch displacement along fault plane produced on salt flats of Great Salt Lake by earthquake of March 12, 1934. (*Photograph furnished by Glenn Walter.*)

large number of small shocks. In the 24 hours following the Japanese earthquake of September 1, 1923, 237 shocks were felt, and during the month of September a total of 720. As these adjustments near completion, an affected area becomes free from shocks and there is a quiet period. Such a period in an area subject to earthquakes is known to be the forerunner of a severe shock, but we have no means of determining positively when it will occur.

Earthquakes Caused by Volcanism.—The movement of lavas and gases within the earth's crust, especially the common spasmodic movement, is another means of starting an earthquake. It has long been known that earthquakes accompany the eruptions of volcanoes. Shocks may occur before an eruption and so are more or less of a warning of volcanic activity, but a greater number of shocks follow an eruption, evidently being due to readjustments within the lavas and the surrounding rocks below the surface. As a rule shocks which accompany vol-

canism are less severe and destructive than those that are due to faulting.

Why Earthquakes Are So Destructive.—A question often asked is why so small a movement (0.5 inch or even 3 inches) as that usually accompanying an earthquake shock should cause so much damage. The answer is that the destructiveness of the earthquake is not due to the amount but to the great velocity of the movement. As the wave moves forward objects upon the surface are set in motion. What happens to tall objects may be illustrated by considering the fate of a tall tree during an earthquake. The base of the tree moves forward with the wave and this forward movement passes at a much slower rate up the tree.

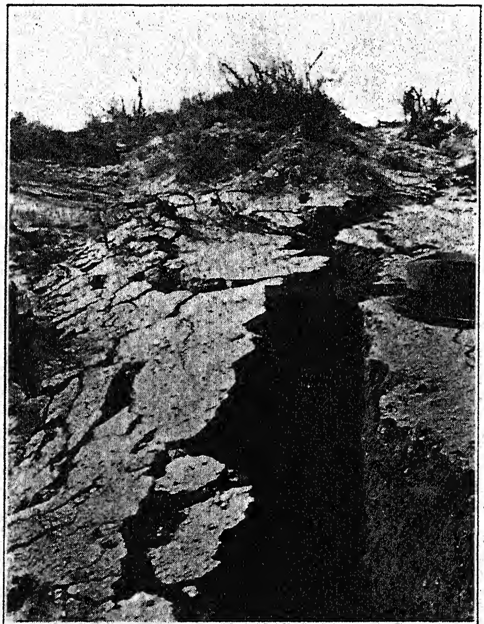

FIG. 323.—Opening produced along fault plane near Great Salt Lake, March, 1934. (*Photograph furnished by Glenn Walter.*)

The forward movement of the ground, however, is immediately followed by the recoil or backward movement, and thus the direction in which the base of the tree was moving is instantly reversed and the backward movement starts up the tree. However, as the top had not traveled so far forward as the base, the quick reversal of direction may snap off the top of the tree. Just so would the top of a tall chimney be snapped off. During the Tokyo earthquake 110 of the 240 chimneys that were over 45 feet high were completely destroyed and more than 40 of those not destroyed were seriously damaged.

Tall buildings, if rigidly built, sway or oscillate back and forth during an earthquake shock, and if poorly built are destroyed (Fig. 324). If a

building can rock or slide upon its base, all of the movement will not be transmitted to the structure and the damage will be less. If a building is not too high and is well built, it will not be seriously damaged beyond the cracking of the walls, breaking of glass, and destruction of the chimneys. The greatest damage to buildings is inflicted upon those located on soft ground, such as that made by filling low places with earth. This ground moves and slips irregularly in various directions, and the buildings upon it, unless very rigidly built, are rocked to pieces.

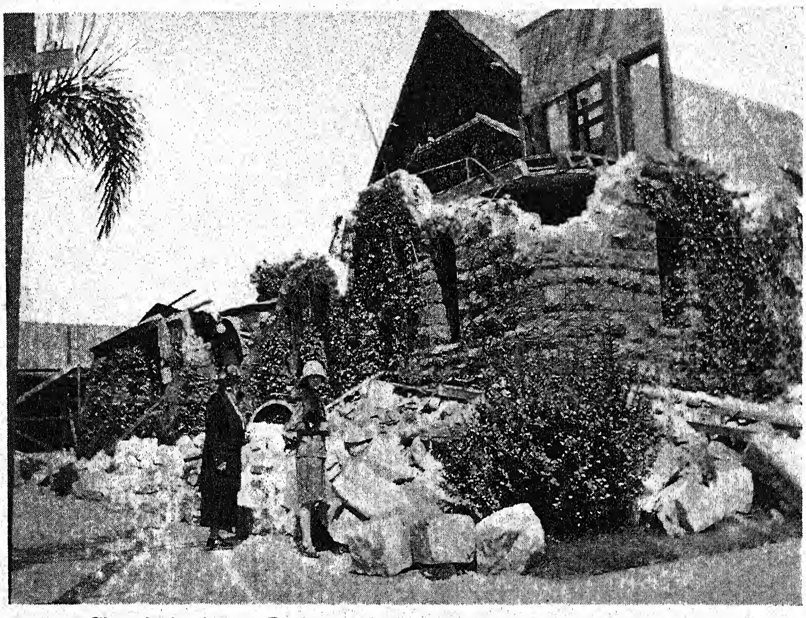

FIG. 324.—Church in Santa Barbara, California, demolished by earthquake of 1925. (*Photograph by P. D. Tarr.*)

The great loss of life in the earthquake at Messina, Sicily, was due in large part to the poor construction of the houses.

The greatest damage inflicted by earthquakes occurs where the wave reaches the surface at an angle of 30 to 50° (*d*, Fig. 318) and not directly over the epicentrum, as in that place the movement is usually up and down.

Aside from the damage due to the earth vibrations, fires cause great destruction of life and property, as do also the sea waves that are produced so commonly by submarine earthquakes or those occurring near the sea shore. These waves are called *tsunamis*.

Fires that start in towns or cities during or following an earthquake shock cause such terrible destruction because the water mains have usually been severed by the earthquake and the fire-fighting apparatus destroyed. At the time of the Tokyo earthquake thousands of lives were

lost in the accompanying fire, which burned over an area of 8,300 acres. Fires covered an area of 2,300 acres in San Francisco during the earthquake of 1906.

Tsunamis are caused by the transmission of the movement of the solid rock to the mobile water above. Such waves are of exceptional size and travel away from the epicentrum of the earthquake. If the wave reaches the shore while still of considerable magnitude, it may cause great damage. In a shore indentation having converging walls tsunamis commonly attain heights of 10 or 20 feet. The one accompanying the Lisbon earthquake reached a height of 60 feet due to such a cause. The velocities of tsunamis have been estimated at 300 to 400 miles per hour.

Some Important Earthquakes.—The number of human lives destroyed by earthquakes will never be known. It must be several millions. In view of the fact that the exact number of lives lost in the recent earthquakes in China and Italy is not known, it is not surprising that the figures throughout the last 1,000 or more years are no more than estimates. The list of earthquakes that are known to have been destructive to human life is a long one, as the table on the next page shows, but the number will increase faster in the future than it has in the past, due to the steady increase in the world's population and its growing congestion in earthquake areas.

Probably the most destructive earthquake that ever occurred was the one on February 2, 1556, in the provinces of Shansi, Shensi, and Honan in north-central China (see table). Nearly 200 years later, in 1731, another earthquake occurred in the same region—this time at Peking. China has since been visited by two terribly destructive shocks, both of which occurred in the same area but in the province of Kansu. As can be determined from the table, the total loss of life during these four earthquakes approximates 1,226,000.

The earthquakes in the Kansu province were in an area of loess, which was loosened and moved in such great quantities that the Chinese, lacking a word for "landslide," described what happened thus: "The mountains walked" (Shan tso-liao). The loosened loess moved down the hillsides into the valleys, burying houses, villages, and rivers. Great numbers of people lived in caves in the loess and in mud-brick houses. Their fate can easily be imagined.

Southern Japan was visited by a tremendous earthquake on September 1, 1923. The main shock center was only about 55 miles south of Tokyo, and therefore the destruction and loss of life were tremendous. The shock came at noon on Saturday when there was a vast number of people in the business districts. Block after block of houses went down, and the fire that broke out immediately burned those who were imprisoned in the falling structures. The cause of the earthquake is believed to lie in the fact that a fault zone has developed between Japan and the great

MORTALITY CAUSED BY THE MAJOR EARTHQUAKES FROM 577 TO 1927

Place	Year	Number killed
Constantinople, Turkey	577	10,000
India	893	180,000
Georgia (Caucasus)	894	20,000
Irak, Arabia	1007	10,000
Tabriz, Persia	1050	50,000
Catania, Sicily	1137	15,000
Persia	1139	100,000
Syria	1158	20,000
Catania, Sicily	1169	14,000
Kiangsi, China	1333	10,000
Naples, Italy	1456	60,000
Lisbon, Portugal	1531	30,000
China (Shansi, Shensi, and Honan)	1556	830,000
Naples, Italy	1626	70,000
Calabria, Italy	1638	10,000
Sicily and Catania, Italy	1693	100,000
Yeddo (present city of Tokyo), Japan	1703	190,000
Algiers	1716	18,000
Peking, China	1731	96,000
Kashan, Persia	1755	40,000
Lisbon, Portugal	1755	60,000
Syria	1759	20,000
Calabria, Italy	1783	80,000
Central America	1797	40,000
Caracas, Venezuela	1812	12,000
Sumatra	1815	20,000
Aleppo, Syria	1822	20,000
Mt. Ararat, Armenia-Persia	1840	10,000
Naples, Italy	1857	12,300
Calabria, Italy	1857	10,000
Mendoza, Argentina	1860	12,000
Peru	1868	20,000
Khorassan, Persia	1871	30,000
San Jose de Cucuta, Colombia	1875	16,000
Hondo, Japan	1891	20,000
Kangra, Punjab, India	1905	20,000
Messina, Sicily, and vicinity	1908	164,000
Central Italy	1914	12,000
Central Java	1919	10,000
Kansu, China	1920	200,000
Persia	1923	20,000
Japan	1923	250,000
Kansu, China	1927	100,000
Total	....	3,141,300

ocean deep that lies 200 miles to the east. The epicentrum of the earthquake was located in this zone of weakness.

There have been several earthquakes in the United States within the last 130 years, but fortunately none have been especially destructive of life. One at New Madrid, Missouri, began December 16, 1811, and continued until March 16, 1812. During that interval more than 1,800 shocks of a wide range of intensity were noted. The disturbance was on the flood-plain of the Mississippi River, and was accompanied by irregular and local settling of the land and the formation of several lakes. Cracks were formed and filled with material from below.

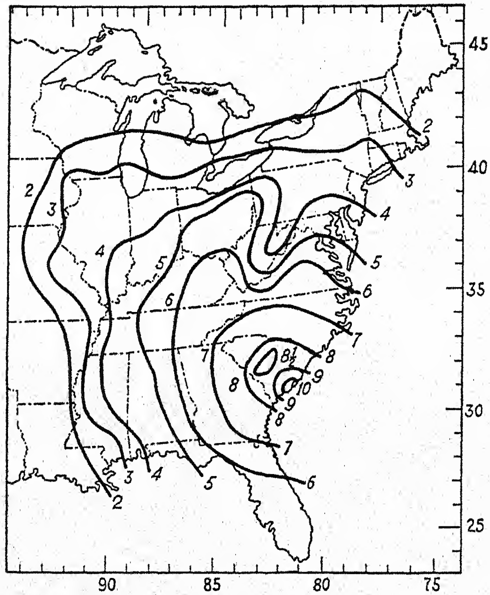

FIG. 325.—Map showing immense area affected by earthquake at Charleston, South Carolina, in 1886. Numbers indicate intensity of shock (see table, page 294).

An earthquake occurred at Charleston, South Carolina, on August 31, 1886, the shock of which was felt over an area of 2,000,000 to 3,000,000 square miles (see Fig. 325). Another earthquake, which was more destructive of life and property occurred in San Francisco, California, on April 18, 1906. It was caused by a horizontal movement along a fault plane more than 300 miles in length (Fig. 326). The greatest damage done was in San Francisco and this damage was primarily due to fire, as the mains carrying the city's water were severed.

Geological Effects of Earthquakes.—The geological effects of faulting are often ascribed to earthquakes, but it must be remembered that an earthquake is only the vibration of the earth resulting from the faulting. Some effects of the earth vibrations are that underground drainage is changed, springs being closed at one point and opened at another; small

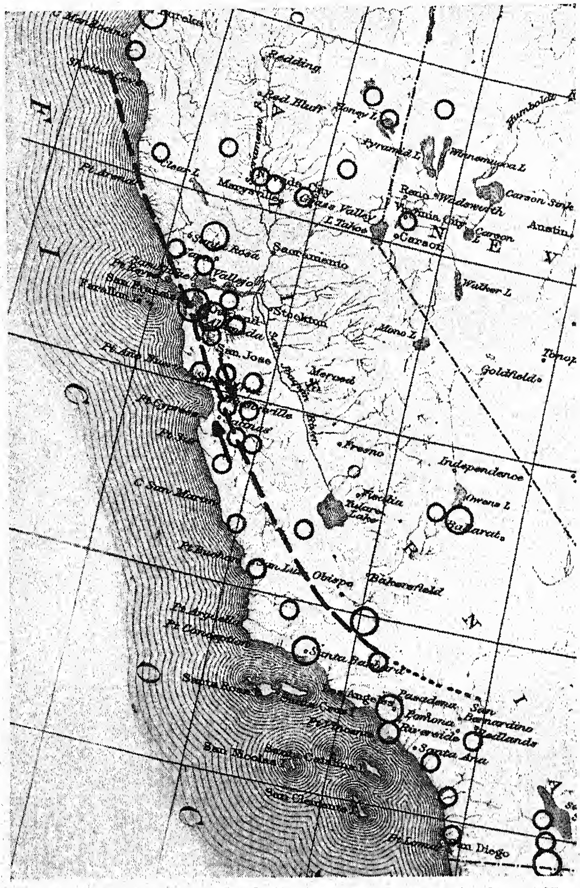

Fig. 326.—Map showing position (dashed line) of San Andreas Fault along which occurred the movement that caused the San Francisco earthquake of 1906. (*Data from various sources.*) Also, approximate location (circles) of the major earthquakes known to have occurred in California. (*Data from N. H. Heck, Scientific Monthly,* 1930.)

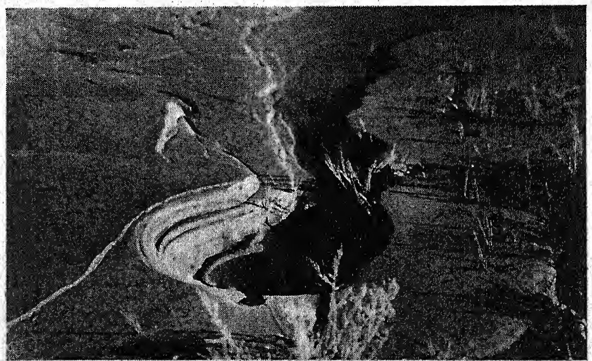

Fig. 327.—Small crater (two days after earthquake) from which sand and salt water were ejected during earthquake at Great Salt Lake, March, 1934. (*Photograph furnished by Glenn Walter.*)

craters are produced from which water, gases, mud, and sand may be ejected (Fig. 327) or into which sand and mud may be washed; and a settling of the ground takes place, resulting in the formation of ridges and depressed areas on the surface. These low places may later become the sites of lakes, as Reelfoot Lake in Tennessee formed after the New Madrid earthquake. Vibrations may also start landslides (as those in the loess in China) and so act further in reshaping the features on the surface of the earth.

As we have seen, the immediate results of earthquakes are destructive to man; but it may be that in the long run they are a protection to him; because, since the vibrations relieve stresses and strains in the rocks, the earthquake may be the safety valve that prevents even greater and unimaginable catastrophes.

PART II

HISTORICAL GEOLOGY

CHAPTER XV

HISTORICAL GEOLOGY

INTRODUCTION

In the first part of this volume we have studied the materials on the earth, the forces at work on the inside and outside of the earth, and the features resulting from these forces. These studies might well have been grouped under the headings Chemistry of the Earth and Physics of the Earth, the former including the study of the earth materials, the latter the study of earth forces.

For the most part the illustrations for these earlier studies have been actual conditions and events that have existed or taken place during times of recorded human history. Most of them could be duplicated at any time and might be observed by anyone who would travel to places favorable for their study.

Historical geology, the succession of events through which the earth has passed, is deciphered by applying the facts and principles reached in the study of the chemistry and physics of the earth to the recorded effects which past events have left in the earth. It is only by constantly reviewing the present-day variety of conditions and their characteristic effects that the beginner can hope to penetrate the haze obscuring past events and conditions as recorded in the rocks. For instance, we have learned that glaciers are today breaking up rock in a distinctive way and are accumulating the débris in a characteristic manner. If glaciers have existed in past geological times, the sediments formed by them should indicate their glacial origin even though the sediments were consolidated into beds of rock and deeply buried under the record of later events of the same region.

Just as one may study any special phase of human history, various successions of earth events may claim our attention. For the beginner it is desirable to push historical inquiry over the entire field as far back as direct or even indirect evidence extends. No matter how meager this early evidence may be, it affords a background against which later and better-recorded events can be more fully appreciated. As a geologist one may legitimately inquire into earth events as far back as the earth was in any way comparable with the earth today. Of the remote times the records are few and poorly preserved, in many cases completely discouraging. Even so there is history recorded, history of the birth and infant stages of the earth, a story we may never know with any degree of

certainty. But there can be set up a logical beginning of the story, a beginning which though incapable of proof is entirely in keeping with the details of the part that follows. Every thinking person is interested in the origin of the earth and even in the origin of the universe, but science has no theory for the origin of the universe and the origin of the earth falls within the province of the astronomers.

Fossils.—Fossils are the most useful instruments for deciphering earth history. They are remains or impressions of animals and plants preserved in the rocks. A typical way for a fossil to form is by an animal dying where his remains may become covered with mud. The soft parts decay and the hard parts are encased firmly in the mud. If the animal be a clam the inside of the shell may also fill with mud. Animals' remains that have been preserved in recent time are not called fossils; the remains must be buried for thousands of years before they become true fossils.

The hard parts of the animal may be replaced slowly by other materials, *i.e.*, become petrified. The replacing materials are in most cases calcium carbonate, or silica, or iron sulfide. Animals of Pleistocene time have been found frozen in the ice; many insects are preserved in amber, the gum of plants; and fossil footprints are commonly found in sandstone and shale.

Fossils enable one to classify animals and plants into species, to make differentiations among them on very minute characters. Every formation that originated where animals or plants were living is likely to contain fossil remains of them, and they are the geologists' most trustworthy historical material.

CHAPTER XVI

ORIGIN OF THE EARTH

Many hypotheses have been formulated to explain the origin of the earth but only a few have been sufficiently elaborated or supported by broad knowledge of the earth and the heavenly bodies to warrant serious consideration. Of those that do deserve attention two are outstanding, the nebular and the planetesimal. They are directly opposed to each other in almost every point, and are typical of all other hypotheses of their class. In general these two may be thought of as typifying the hot and cold origins respectively. Modifications and combinations of one or both of these have been elaborated and have ranked as independent hypotheses. Under any of the hypotheses of earth origin the recorded geological history would not be very different from that demanded by the nebular and planetesimal hypotheses.

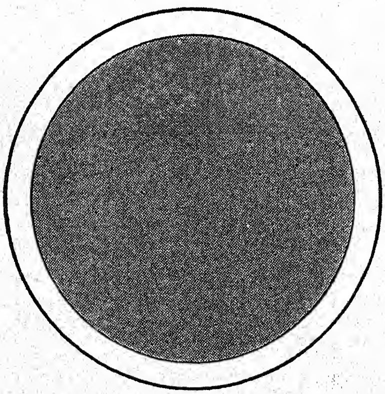

FIG. 328.—The star from which the solar system originated at a stage after the first ring had separated from the parent nebula and before the second ring separated. Diameter of the sun at this stage about five billion miles.

The Nebular Hypothesis.—The first reasonable hypothesis for the origin of the earth was proposed in 1755 by Immanuel Kant, professor at Königsberg. His attempt to account for the rings observed about Saturn led to the conception which, when amplified by others, became the nebular hypothesis. The astronomer Laplace brought to the hypothesis the necessary background of scientific data and was really the first to state clearly the complete series of hypothetical steps leading up to our known solar system. For this reason the nebular is often designated as the Laplacian hypothesis.

As the name indicates, the solar system—the earth and the other eight planets, the satellites, asteroids, and the sun itself—originated from a nebulous mass. The hypothesis, as modified to meet later scientific developments, stipulates that originally all the material of the present solar system was combined into a single unit. This unit was an extremely hot, highly tenuous, rotating sphere of gases, expanded to a size even greater than the diameter of the orbit of Pluto, the outermost planet. If these assumptions be granted the sphere would shrink in size and increase in speed of rotation, and a stage might follow in which the speed

of its equatorial belt would be so great that an equatorial ring would be left behind as the main mass continued to shrink. Shrinking and speeding up of the sphere left behind nine rings. Each of these collected into a rotating sphere which revolved about the central body in the path of its ring, its present orbit. The remains of the original gaseous sphere is the sun; the rings, modified into nine spheres, are the planets. Each of the planets in turn shrank and left one or more rings revolving about it, which remained like the rings of Saturn or consolidated and became satellites like the moon.

Turning to the details of planet evolution as typified by the earth: In its first stage it was a hot gas, the gas condensed to a liquid, a solid crust formed on the outside, and pressure from the weight of the mass

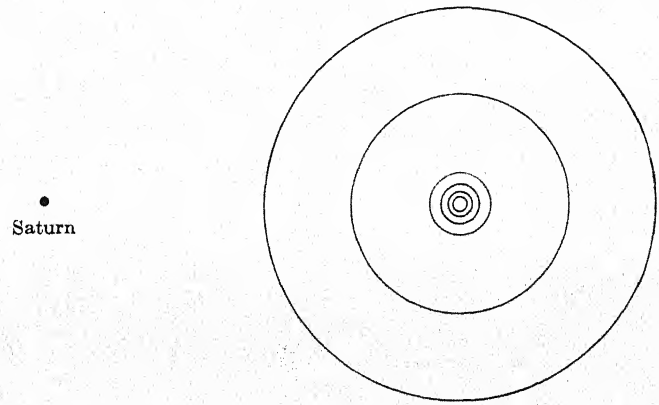

Fig. 329.—The parent nebula has shrunk to the size of the orbit of Mercury, the innermost planet. The Mercury ring has not separated. The outer ring has condensed to a globe (Saturn), shown as a black dot.

caused it to become solid at the center. The earth, with a solid center, crust, and liquid or semiliquid zone below, is in the stage where earliest geologic records might be preserved. In later development most of the interior solidified.

The hypothesis is simple and its implications are clear and satisfying if not too carefully scrutinized. So many things are now known about the earth and the heavens that were unknown in the days of Laplace that the task of bolstering and modifying the nebular hypothesis has become burdensome. When modified to fit present knowledge it has lost nearly all of its distinctive features and really deserves an altogether new name.

The Planetesimal Hypothesis.—Astronomers have long been interested in spiral nebulae, which are assemblages of stars and nebulous matter of unbelievably great size at distances from the earth measured in thousands of light years.

Early in the twentieth century the geologist Chamberlin and the astronomer Moulton conceived the idea that a small nebula of this type

gave origin to the solar system and worked out the hypothetical steps leading from a small spiral to a planetary system.

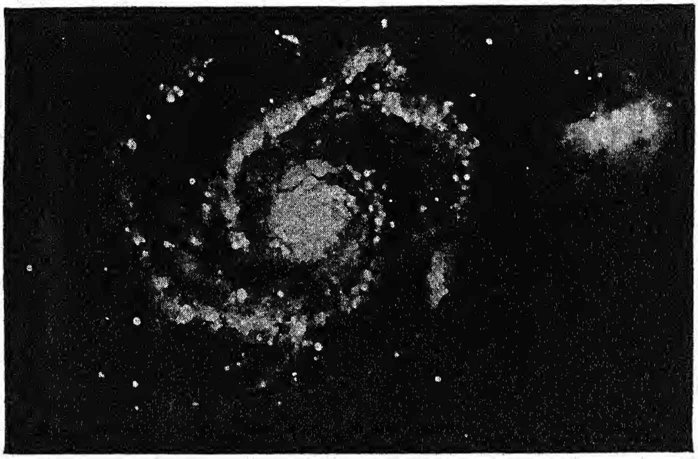

FIG. 330.—A spiral nebula showing the central sun-like mass and spirally outflung arms with knots. A form similar to this was postulated by the planetesimal hypothesis, as an early stage in the evolution of the solar system. (*R. C. Moore, Historical Geology, from a Lick Observatory photograph.*)

They assumed that the spiral nebulae are made of gases and solids and that they resulted from the partial wreckage resulting from the close approach of two great stars. In this type of nebula there is a comparatively dense central mass about which curl two opposed spiral arms, and they assumed that the central mass is the major portion of the wrecked star and the arms represent the wreckage. They assumed also that each particle in the arm, no matter what size, has an individual path about the central mass and is following this path at tremendous speed.

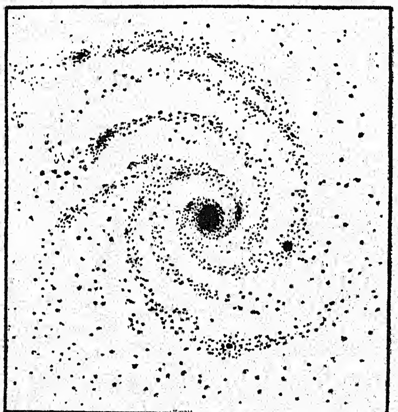

FIG. 331.—A stage in the evolution of the solar system when many of the planetesimals have been gathered up by the larger nuclei and some of the nuclei have reached planet-like proportions.

If we conceive of the wreckage in the spiral arms as varying greatly in size, with a few exceptionally large masses made up of either closely associated fragments or a single unit, it is evident that as each unit moves in its orbit it must cross and recross the paths of countless other units. Where the paths cross there is opportunity for the larger units to become larger by overtaking or being overtaken by the smaller. Ultimately the wreckage would be cleared up and combined in a few bodies (planets

chiefly) whose orbits would be too nearly circular to cross one another. The satellites are details in the clearing-up process—bodies that have come so near a planet as to be controlled by the larger body but with sufficient speed of revolution to prevent their being drawn into the planet.

It is evident that the two contrasted hypotheses demand different explanations for the origin of the atmosphere, the water, and the heat of the earth. Perhaps a modification of the planetesimal hypothesis made by Jeffreys, that the original nuclei of the planets were of planet size in the beginning, should be accepted for some of the planets. Barrell thought that the infall of units in the clearing-up process was sufficient to produce enough heat to fuse most of the infalling material, and that suggestion also seems reasonable.

The early history of the earth under the two hypotheses may be compared as follows:

Nebular	Planetesimal
Earth began as a large globe of gas.	Earth began as a small aggregate of solid rock, or (Jeffries modification) as a great mass of sun material.
Earth was originally very hot.	Earth was cold but developed heat.
Earth has always been a cooling body.	Earth has usually been a heating body.
Earth originally had a very large atmosphere.	Earth originally was atmosphereless.

The explanations of earth origin are called hypotheses because they are proposed explanations—they have not reached the class of theories. The hypotheses are supported by many facts but may be abandoned with the growth of astronomical knowledge. The planetesimal hypothesis fits geological conditions much better than the nebular. Hypotheses of earth origin are not part of geological science but they have had profound effects on it.

CHAPTER XVII

DAWN OF EARTH HISTORY

The evidences of the dawn of geologic history are locked up in the oldest rocks; in discovering this history the geologist must determine which rocks are the oldest. After he has found ways of distinguishing older rocks from younger he should be able to explain the methods to the nongeologist. In making the explanation he would be fortunate to stand

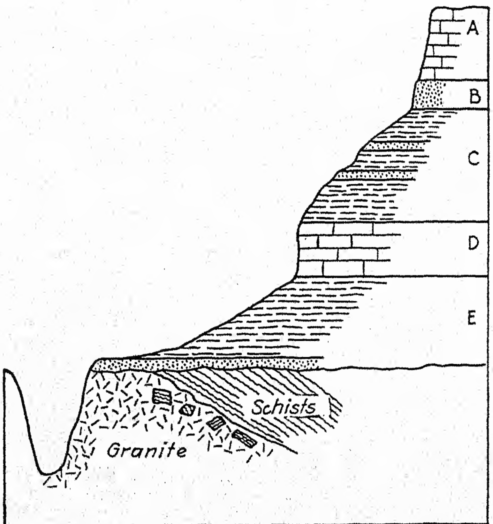

FIG. 332.—A section of the Grand Canyon of the Colorado River with a depth of 5,000 feet.

on the brink of the Grand Canyon of the Colorado River and examine the layers of rock that make up the Canyon walls. The rocks *A* at the top must be younger than the rocks *B* below (Fig. 332). *A* must have been deposited on something and the present association shows that the something was *B*. *B* in turn must have been deposited on *C*, which must have been present before *B* was deposited. *A* is 400 feet thick, made up of more than 400 beds, and each higher bed of *A* must be younger than the bed on which it rests. The Canyon section comprises more than 4,000 feet of sedimentary rocks in which we are able to determine without question which are the older.

The lowest sediments rest on an eroded surface of granite. Not only is the surface eroded, but several thousand feet of the granite had been

removed by erosion after the granite solidified and before the sandstones resting on it were deposited.

We may compare this to the history that one might read in an old structure like the Chinese Wall. It has been mended in places—a new wall has been built on the jagged remains of the old wall. The method of laying the new wall is different from the old and the rocks of the new wall are of a different kind. It is evident that the new part of the wall is the younger—the old wall had to be there as a foundation of the new. History was in the making between the old and the new. What destroyed the upper part of the old wall? Was it merely the work of the elements or of man? If it were the work of the elements, the time was long, hundreds of years, and the wall itself tells nothing of the history of those hundreds of years. The same is true of the gap in the Grand Canyon wall. Thousands of feet of granite were eroded away and the only record of the time is the gap itself.

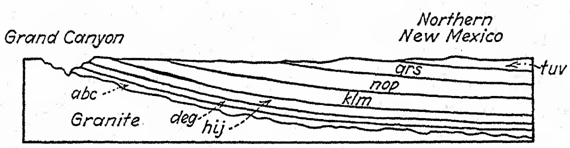

Fig. 333.—The rocks eastward from the Grand Canyon for a distance of 400 miles. The letters represent various kinds of fossils, *a, b, c,* the oldest; and *t, u, v,* the youngest.

In studying present-day erosion it is evident that a rate of 1 foot in 5,000 years is rapid. If we apply the modern rate to the granite removed in the Grand Canyon district, we have a gap of millions of years recorded only by erosion.

Eastward from the canyon other rocks overlap those that form the rim of the canyon. These rocks must be younger than the rim rocks and they are in turn succeeded by still younger rocks. One may walk eastward on the bare rocks of the various formations and find that he must constantly step up on to younger rocks. They are no longer in one great canyon, but overlap as one board may be made to overlap another. More than 10,000 feet of these beds appear above the rim rock of the canyon in a distance of 200 miles east. We have discovered no history in going over these rocks save that conditions for sedimentation were present when they were formed. Referring back to the study of sedimentation, with a possible average of 4,000 years to each foot of rock, one may presume that he is on rocks 40,000,000 years younger than the rim rocks. To the geologist the outline of the history is clear, but the study has just begun.

Our object was to find a record of early geologic history, and the oldest rocks that have been seen were the granites in the bottom of the Grand Canyon. Let us return to the bottom of the Grand Canyon and try to find rocks older than the granite. The Colorado River has cut

down in the granite for more than 1,000 feet and the cutting took place later than the cutting of the canyon in the sedimentary rocks that overlie the granite. The granites were not exposed to weathering before the canyon was cut in them. The younger rocks above have been exposed to weathering in the canyon walls longer than the granite and may look older and more extensively weathered than the granite.

However, we have established the relative ages of the granite and the overlying rocks and we know that the top of the granite which forms the eroded surface is millions of years older than the sandstones and conglomerates that lie on the eroded surface. Is the granite the oldest rock exposed to the observation of man? If we could take a trip such as Major Powell made through the canyon, we might be able to find older rocks in the canyon itself.

Rocks Older than the Granite.—Suppose that a geologist goes up the canyon from Bright Angel Trail and finds that the granite continues for a hundred miles. The granite itself furnishes nothing to indicate age, but at one place the geologist finds that great masses of gneisses and schists are in the walls and that the granite contains blocks of schists and gneisses. The granite reached its present association as lava and in order to contain within itself the blocks of schists and gneisses the blocks must have been part of the wall rock through which the lava came. The gneisses and schists were not only solid rock before the lava that formed the granite appeared, but were metamorphic from regional metamorphism (Fig. 332). They are much older than the granite and we have traced geologic history to a period preceding the formation of the granite.

Oldest Rocks Known to Geologists.—The canyon furnishes us no older rocks than the gneisses and schists and no evidences concerning them; but if we may go to the region northwest of Lake Superior we shall find the same association of gneisses, schists, and granites as in the canyon and in addition we can prove that some of the schists have been derived from shales. Before the granites formed there were sedimentary rocks of great extent and thickness formed of materials derived from complete chemical weathering of complex rocks. Before the granites were intruded the shales had undergone regional metamorphism and had become schists. Geologic time, as represented by the schists, goes back millions of years before the granites were formed and the schists derived from the shales seem to be the oldest rocks known to geologists.

Fossils in the Grand Canyon Rocks.—The evidences thus far considered in earth history tell us very little of what elapsed during early geologic time. Perhaps we had better return to the Grand Canyon and get more information. An examination of the sandstones and conglomerates overlying the granite reveals remains of animals in the rocks. The remains are called fossils and consist of shells and impressions of inverte-

brate animals. The man who knows invertebrates recognizes the shells as belonging to sea animals. The remains of the sea animals have been found in thousands of places in the rocks and no remains of land animals have been found with them. In some places the shells of sea animals make up most of the rocks. There is no escape from the conclusion that the rocks were formed in the seas and that the seas occupied the regions at the time that the rocks were formed.

In the Grand Canyon region at the Bright Angel Trail, after the granites had been eroded for millions of years the ocean waters transgressed over them. The waters contained many kinds of animals, similar to those that live in warm water and are not found in the colder climates.

In the rim rock of the canyon great numbers of fossils have been found. They too were marine and lived in warm waters, but they are all different from the animals that lived in the older time. A complete change had taken place in life from the time the older rocks were formed to the time the rim rocks formed. However, close relationships exist between the animals of the two periods and it seems that the animals in the higher rocks developed through many changes from those in the lower. None of the animals in the higher rocks are like modern animals.

Fossils from Younger Rock.—In the rocks 200 miles east of the canyon, which we determined as separated by 10,000 feet of rock from the canyon rim rock, many fossils occur and all are different from the rim-rock fossils. All of the fossils in the rim rock are small and nearly all are invertebrates. In the New Mexico rocks some large reptiles occur; the fossils are all nonmarine and are forms that lived in warm climates. None of them is like modern forms.

Extensive study of fossils has brought to light many things about geologic history and evolution of life, but our purpose at present is merely to examine some of the things that help to determine the history of the earth. We may formulate from what we have learned part of the history preserved in the Grand Canyon region. Geologists have determined the history of the earth by visiting almost all accessible regions and studying them in detail. Probably the area in which you are working has had years of study by geologists and has had many articles written about its geology.

Eras.—Geologic history is very long, and in order to make it readily understandable geologists have made several subdivisions. Five eras (subdivisions) are recognized on the basis of great breaks in the physical history, and resulting effects on animals and plants. The eras were terminated by great continental uplifts and mountain making, which form the great natural breaks. They were named from the stage of development of the fossils found in their rocks. The eras are listed below in the order from youngest to oldest. They have been subdivided into periods, and the periods into still smaller divisions.

Cenozoic	Meaning recent life.
Mesozoic	Meaning life of intermediate time.
Paleozoic	Meaning old life.
Proterozoic	Meaning earlier life.
Archeozoic	Meaning ancient life.

PRE-CAMBRIAN ARCHEOZOIC AND PROTEROZOIC

Owing to the difficulty of deciphering the history of the older eras the Proterozoic and Archeozoic will be treated together and called pre-Cambrian as coming before the oldest period (Cambrian) of the Paleozoic.

Wherever the base of the sedimentary series of rocks is accessible it rests on metamorphic or igneous rocks. We have studied such contacts near the bottom of the Grand Canyon and they have been studied in thousands of places. The old igneous and metamorphic rocks are at the surface over nearly one-fifth of the land. (Consult your geologic map for the areas of outcrop of pre-Cambrian rocks.) The area in the Great Lakes–Hudson Bay region is the largest in the world. The area east of the Appalachian Mountains is important. Nearly every chain of the Rocky Mountains has a core of pre-Cambrian igneous or metamorphic rock. In several places in the Mississippi Valley the metamorphic and igneous rocks protrude through the younger sedimentary rocks—in the Ozarks of Missouri and in the Arbuckle Mountains of Oklahoma.

If you go to the top of Pikes Peak, probably the best-known peak in the United States, you will find it made up of pre-Cambrian igneous rocks, but if you go to Mount Rainier, probably the most imposing mountain in the United States, you will find it made of igneous rocks of recent date. If you cross the United States from Boston to Los Angeles through Albany, Cleveland, Chicago, Kansas City, Pueblo, Albuquerque, and Needles, you will not see pre-Cambrian rocks west of Albany along the route excepting in three or four small areas in New Mexico and Arizona. Many of the great mountains of the other continents have pre-Cambrian rocks exposed at their summits.

Kinds of Rocks of Pre-Cambrian.—If you were to make a collection of Archeozoic rocks from almost any large area you would get hundreds of varieties of igneous and metamorphic rocks but in most regions you would look in vain for limestones, shales, sandstones, or any other kinds of sedimentary rocks. In the Proterozoic sedimentary rocks dominate but igneous rocks form a larger proportion of the whole than in any later era.

Metamorphic rocks that were derived from sediments are abundant. Sedimentation in the pre-Cambrian time was much as it is now though weathering may not have been so complete owing to lack of land plants. There is no evidence to show that the climate of pre-Cambrian time was greatly different from that of the present, and such climate would produce the same type of weathering as at present. We know slates and schists

Eras	Periods	Events	Life
Cenozoic	Cenozoic	Glaciation	Rise of man. Extinction of primitive types of mammals. Development of modern kinds of mammals.
		Rocky Mts. and other Western mountains Great lava flows	Appearance of primitive man. Modern plants throughout the Cenozoic. Appearance of modern species of mollusks. Beginning of modern types of mammals
Mesozoic	Cretaceous	Rocky Mts.	Culmination of reptiles. Culmination of complex sutured cephalopods in America. Great abundance of clams, particularly of the oyster type. Appearance of flowering plants
	Jurassic	Sierra Nevada Mts.	Great development of many kinds of reptiles. First appearance of birds. Mammals small and rare. Culmination of complex sutured cephalopods in Europe
	Triassic	Aridity Volcanism	Appearance of dinosaurs, flying reptiles, swimming reptiles, and mammals. Rise of complex sutured cephalopods
Paleozoic	Permian	Glaciation Appalachian Mts. Aridity	Development of many kinds of strange reptiles. Disappearance of trilobites. Great reduction in life in the later part of the period
	Pennsylvanian		The first reptiles and insects. Culmination of Paleozoic plants
	Mississippian		Great development of sharks and crinoids. Plants become abundant
	Devonian		Development of fishes with rise of all main groups of fishes. Development of paired limbs. First forests. First amphibians. Old-age characteristics in trilobites
	Silurian	Aridity	Appearance of scorpions, air breathers. Fishes rare. Crinoids important. First coral reefs
	Ordovician	Taconic Mts.	Rise of cephalopods. Appearance of fishes
	Cambrian		Trilobites and brachiopods dominant. First abundant fossils
Proterozoic		Glaciation Volcanism	Some fossils, but all poorly preserved and most of them nondeterminable. Algae, the most common form of life
Archeozoic		Volcanism	No fossils, but some indications of life

FIG. 334.—A table showing geological eras, periods, main physical events, and some of the most important life events.

that must have come from shales and the shales from muds, of quartzites that came from sandstones, of marbles that came from limestones.

But it is clear that igneous activity was much greater during pre-Cambrian times than it has been since and that earth movements, which, together with volcanism, produced the metamorphism, were on a larger scale than they have been since. The pre-Cambrian was a time of dominant volcanism with gradual evolution toward a period of dominant sedimentation and little volcanism.

Life of the Pre-Cambrian.—In the late pre-Cambrian impressions of low types of plants (algae related to the pond scums that are common at the present time) are preserved in the rocks. The algae were abundant in some places, but their impressions are faint and obscure. Probably no plants existed on the lands.

In late pre-Cambrian rocks impressions and fragments of a few kinds of very primitive animals appear. All of them lived in the waters and

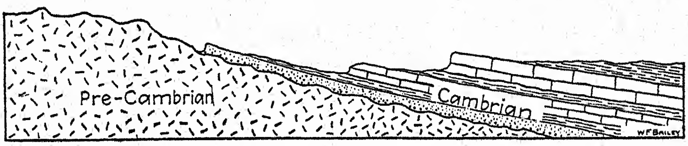

Fig. 335.—Section of a mountain, showing pre-Cambrian rocks in the core and at the top.

they appear to have been rare. The highest type of life was much below the modern crawfish and most of the forms belonged to the protozoa (one-celled animals). The ameba, which is widely distributed in pond waters, is the best modern example of primitive life. It consists of one cell and it resembles a droplet of oil, but has the power of moving very slowly, of taking in and assimilating food, and of reproduction. Animals like the ameba lack coherence enough to make any impression on soft muds and they could not leave fossil remains. Probably types of life like the ameba lived for millions of years before anything higher developed and no trace of the earliest types of animal life will ever be found in the rocks.

For a long time pre-Cambrian rocks were known as Azoic or without life; the first traces of life were found in them only a few years ago. Here are the oldest records of life, the beginnings of life history that may be read. The amount of pre-Cambrian rocks that are not metamorphosed is small and the metamorphic process destroyed most evidences of life. But even in the nonmetamorphic rocks fossils are so obscure and rare that only a few geologists have ever found any of them in the field.

Pre-Cambrian life seems to have existed in swampy areas near the sea margins. The strictly marine rocks rarely contain fossils and it is scarcely conceivable that the primitive life could have lived on land.

Plants must have originated before animals as animals depend entirely on plants for their food. Animals do not have the power to get

their food directly from mineral matter and all must depend on plants.

Earth's Surface in the Pre-Cambrian.—At the dawn of geologic history the earth must have been a very uninviting place. The entire surface was made up of rocks unrelieved by colors of plants. The surface was more jagged than in recent times, for plants help to weather off the edges of rocks and their presence tends to soften the appearance of irregularity. The lands must have been strangely silent with no animal present to make its own peculiar noise.

The presence of active volcanoes and other types of volcanism in so many places gave to the earth an aspect out of keeping with present-day conditions. It should not be supposed that the earth was hot owing to the volcanism or that volcanism was prevalent over the entire earth at the same time. Volcanism may have been absent from areas as large as the United States for tens of millions of years.

Climate.—At some periods the climatic conditions were more rigorous than in recent times. Late in the pre-Cambrian a continental glacier had its southern margin not far north of the Great Lakes region. Its east-west extent was more than 1,000 miles. The deposits made by the glacier are now solid rock, in places hundreds of feet thick. The deposits are very irregular in thickness and are composed of boulders, pebbles, sand, and clay. Many of the boulders have flat surfaces and some of the flat surfaces bear scratches. The evidences of glacial origin are not as clear as in the late glacial deposits but they are so clear that no geologist doubts them.

Duration of Pre-Cambrian.—The length of pre-Cambrian time seems to have been nearly two billion years. The best geological clock is the one supplied by the chemist, who has been able to compute the rate of change of atoms of radioactive minerals to atoms of lead. By this clock it has been determined that some Archeozoic rocks formed nearly two billion years ago.

Economic Products.—In Chap. V the origin of several types of ore deposits is discussed and the importance of igneous intrusions in inducing ore deposits is mentioned. The pre-Cambrian is the most important part of the geologic column for ore deposits.

Iron.—Iron is the most important metal and the pre-Cambrian rocks furnish more than half of the iron used in the world. The largest deposits of iron ore in North America are in the Lake Superior region and all are pre-Cambrian in age. The mines of Minnesota and Michigan furnish about 80 per cent of the yearly output of iron ore in the United States and about 40 per cent of the output of the world is mined in this country. The ore mineral is hematite (Fe_2O_3) 70 per cent iron and 30 per cent oxygen. The ore mined is about 70 per cent hematite and 30 per cent rock of other kinds; the actual yield of iron is about 51 per cent of the

material mined. Some of the important Minnesota deposits are mined in open pits and steam shovels are used to take out the ore.

As far as geologists have been able to determine, the deposits originated from hot waters coming from lavas. Highly charged with silica and iron, the waters entered interior seas that existed in the Lake Superior region. The cold water of the seas caused the iron and silica to precipitate and form extensive deposits of siliceous beds highly charged with iron. But the iron content of the rock thus formed was not more than 15 to 30 per cent. In later periods, after the seas had withdrawn and the rocks above the siliceous iron beds were exposed to erosion, ground waters circulating through the rocks dissolved the silica and left the iron until the hematite content was 40 to 90 per cent.

As originally formed the siliceous iron deposits were in extensive beds. The ore deposits left after the solution and removal of the silica are very irregular in outline with thick masses of ore in some places and very little or no ore in others. The best of the deposits cover only a few square miles.

The great iron-ore bodies of Brazil, probably larger than those of the Lake Superior region, are pre-Cambrian in age, as are also the deposits of Sweden and several other parts of the world.

Copper.—The pre-Cambrian rocks of the Lake Superior region bear some of the richest copper ores. For a long time the copper mines of the Lake Superior region of Michigan produced more copper than those of any other region in the world—nearly half of the world production. The Butte, Montana, and Bingham, Utah, districts have surpassed it in recent years, and each of three districts in Arizona has produced more in some years. The ore mineral in the Lake Superior region is native copper; this is the only region in the world where native copper is present in large quantities.

In some respects the metal occurs in peculiar ways. Part of it is in veins as is often the case with copper ores, part of it fills cavities in pre-Cambrian basalt, and part is a cement of conglomerates.

Before the use of modern methods in mining some of the largest masses of copper were mined with difficulty as it cost more to break up such large pieces than to blast out masses of rock small enough to be handled.

Gold.—In recent years gold mining in the Porcupine region of Ontario has become important. One of the largest gold mines in the world is in the pre-Cambrian of this district. Gold is mined from the pre-Cambrian of the Black Hills and many other places.

Other Products.—Nickel and cobalt are important metals that are mined mainly from the pre-Cambrian of Ontario, and asbestos and granite are produced mainly from pre-Cambrian rocks.

Close of Archeozoic.—The Archeozoic era was brought to a close by continental uplift and mountain making. Great batholithic intrusions

invaded and uplifted the older sediments and igneous rocks, accentuating the metamorphism of many of them. The North American intrusions and mountains extended from the Great Lakes region northeastward. The Adirondacks were a small part of the mountainous area.

A period of erosion during which the uplands and mountains were peneplaned preceded the opening of the Proterozoic. This seems to have been the longest period of erosion of geologic history. The reduction to a peneplain of mountains 2 to 3 miles high composed of igneous and metamorphic rocks must have taken many millions of years. Where the Proterozoic seas came in over the peneplain they deposited sediments on the truncated mountain cores.

Close of the Proterozoic.—The Proterozoic closed with continental uplift and mountain making. Some of the mountains were in the Lake Superior region and others in several regions of the world. Batholithic intrusions were on a much smaller scale than in the Archeozoic. In many places erosion reduced the lands to peneplains before the incoming of Paleozoic seas.

CHAPTER XVIII

LOWER PALEOZOIC

The Paleozoic is sharply contrasted with the Archeozoic and Proterozoic in consisting mainly of nonmetamorphic sediments and in containing fossils in abundance.

For convenience in study we may consider Paleozoic history in three parts, as Lower, Middle, and Upper. The era is divided into smaller units called periods, and the two oldest, Cambrian and Ordovician, make up the Lower Paleozoic.

Although we shall not study the periods as such we should know the principles on which they are based. Many times in geologic history seas have advanced over the land, and as they advanced they worked over the mantle rock and sediments brought to them by the streams or eroded by them from their own shores. These sediments were sorted and formed into various kinds of sedimentary rocks. A sea advance constitutes the first event in a period and the sediments laid down became the rocks of the period, but it is only large sea advances that are considered of period value.

CAMBRIAN PERIOD

Why Seas Advance.—The seas would not advance if land and sea bottom remained unchanged. A large up-warping of the sea bottom without a corresponding down-warping of some other part of the sea bottom would cause general sea advance over the lowlands. Such a major up-warping after a time when the shore line had been relatively stationary would be a significant physical change of the earth's surface.

Erosion is taking place on part of the land surface all of the time, and it tends to lower the surface and thus facilitates sea advances. In mature stages of erosion the sea advances would take place only in the marginal valleys, but in old stages the advance would be general. Monadnocks and general elevations would stand out as islands in the advancing sea. The piling up of the eroded material in the sea would raise the sea level very slowly. The general rate of erosion is perhaps 1 foot in 9,000 or 10,000 years and the rise of sea level would be about 1 foot in 30,000 years. This may seem too slow to be of any significance but the total from erosion and deposition would be 4 feet in 30,000 years, 3 feet of down-cutting and 1 foot of sea rise. Some of the periods are 50,000,000 or more years in length. The general elevation of the North American continent is about 2,200 feet. At the ordinary rate of cutting down and sea advance the entire continent would be covered in about 15,000,000

years. However, such a rate could not be maintained. Recall the principles on which the rate of down-cutting by streams depends and you will find that the lower the land becomes the slower the rate of erosion. The more land covered by the sea the less the material furnished

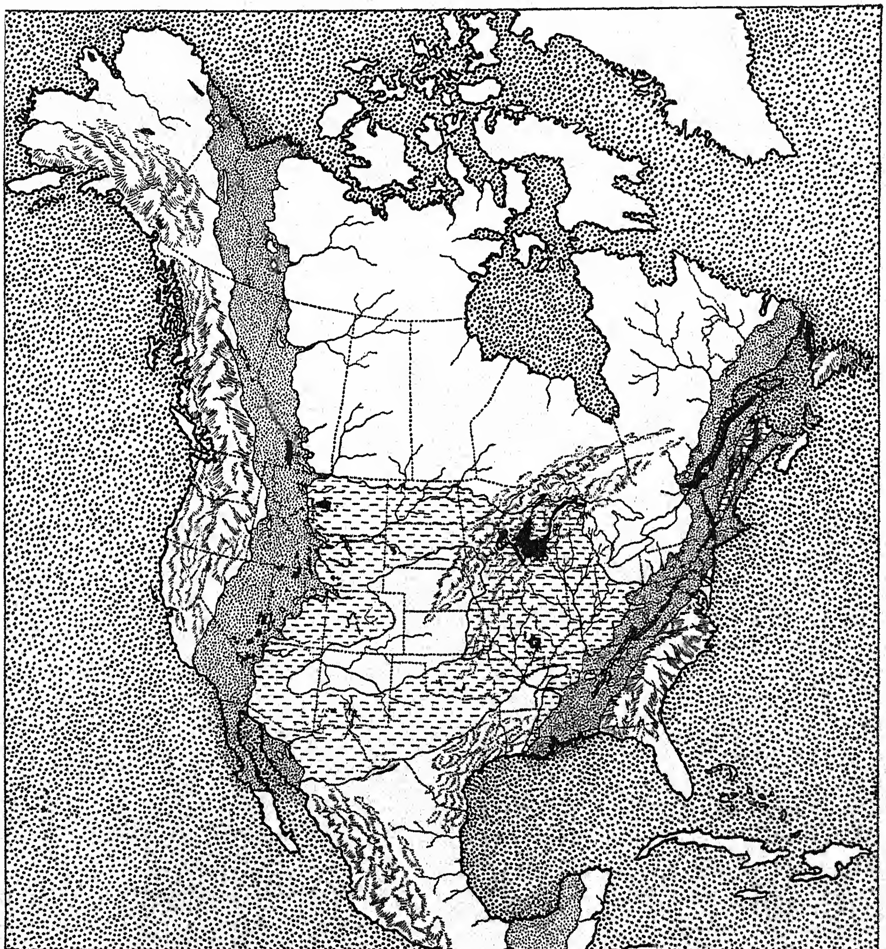

FIG. 336.—Cambrian seas. (*Modified from Schuchert.*) Fine stipple represents early Cambrian epicontinental seas in Appalachian and Cordilleran synclines. Dashed and stippled areas represent epicontinental seas in upper Cambrian. Black represents Cambrian outcrops. The mountains represented were present in lower Cambrian, but those in the interior had been eroded away by upper Cambrian so that seas advanced over part of the region where they had existed.

to the sea and the slower the rise of sea level. The last few hundred feet of the down-cutting of the continent would be almost inconceivably slow and would take a great deal longer than all of the other down-cutting.

Probably the most significant thing in causing an advance of sea on the land is the down-warping of the land itself. Such down-warping is slow

in most cases but not so slow as the rise of the sea due to sedimentation. Where the sea advances and spreads out over large areas of land, the cause of the sea advance must be land warping.

If it were not for up-warping of the land or down-warping of the sea bottom, the lands would long since have disappeared. After the seas have remained on the lands millions of years the physical changes that caused the sea advance, or part of them, might reverse; consequently the seas would begin to retreat. Their withdrawal might be as slow as their advance or might be fairly rapid, geologically speaking. (By "geologically speaking" we mean that the time units should be considered in the light of geologic time rather than in the length of historical time. A year in human history is comparable to a million years of geologic time.)

When the sea withdrawal ceased, or reached the margins of the continent so that no more sediments could be deposited in places where they could later be examined by geologists, the period closed. The rocks of a period are the rocks laid down in the seas from the beginning of one great major advance to the end of one major retreat. Some quibbling and disagreement might arise as to what is meant by major advance and major retreat, but as elementary students we are not concerned with closer discriminations.

Methods of Identifying Sea Advances.—The question arises as to how geologists can determine whether rocks belong to one major advance or another, to one period or another, how they know when the sea retreated or when it advanced. Most of these things have already been treated in the work on physical geology, but they will be emphasized as we proceed with the historical part. We have considered the nature of unconformities without considering their significance. According to definition an unconformity is a relationship between series of rocks in which the underlying series had been eroded before the overlying was laid down. Of course the overlying sediments fit into the irregularities of the underlying and the line of demarcation between the two series is likely to be easily made out. If, then, in the field, you should find a decided unconformity between two series of rocks both of which were marine in origin, you would consider that the lower rocks had been formed in a sea which withdrew and allowed streams or some other agents to erode the surface, that the seas then advanced over the eroded surface, laid down sediments, and formed new rocks on that surface. Would that be the line of boundary between two periods? Where students go into such regions made up of pre-Paleozoic rocks as we have already considered, they find them largely composed of igneous and metamorphic types. Suppose that you should go into such a region and on top of the pre-Paleozoic rocks find a conglomerate made up of pebbles of those rocks, the pebbles fairly well sorted into uniform sizes and into definite beds. Suppose

you should find in the conglomerates some fossil shells of sea animals. (Although fossils are not common in conglomerates they do occur in some places.) In order to get the pebbles of the underlying rock that rock had to be eroded, and very little erosion occurs except above water. Erosion that involves weathering takes place only where the rocks are exposed to the atmosphere. The pre-Paleozoic rocks, then, had been eroded before the conglomerates were formed on top of them. The conglomerates, being fairly well sorted, were laid down in large bodies of water and not merely by streams, glaciers, or some other transporting agents. Containing marine fossils, the large body of water must have been part of the sea. You have here evidence of erosion of the pre-Paleozoic and sea advance over that pre-Paleozoic. The conglomerate constitutes the oldest rock of a period.

The Appalachian Trough.—In the early studies of the geology of eastern North America, investigators found that the oldest rocks of the

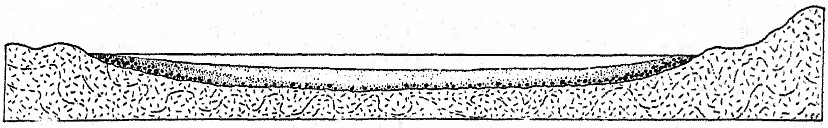

Fig. 337.—Cross-section of the Appalachian Trough showing original position of early Cambrian rocks and their relationship to the pre-Cambrian rocks.

Appalachian Mountain region are conglomerates of the type described laid down on pre-Paleozoic metamorphic rocks. This indicated that the seas had advanced early in Paleozoic time over the region that is now the Appalachian Mountains. Above the conglomerates are sandstones, shales, and some limestones, in a series ranging up to thousands of feet in thickness. Another great unconformity at the top of the series indicates withdrawal of the sea and erosion of that series of rocks. The conglomerates, sandstones, and shales can be traced the entire length of the Appalachian Mountain region but laterally their extent is small, about the width of the Appalachian Mountains. Their original position and relationship to the underlying rocks is shown in Fig. 338. It is evident that the underlying rocks were bowed down into a syncline and that the conglomerates, sandstones, and shales were deposited in the syncline. The syncline has now come to be known as the Appalachian Geosyncline, more commonly called the Appalachian Trough. At one time it was difficult to convince even students who knew something of geology that the Appalachian Mountain region had been the site of arms of the sea, but the outlines of the geosyncline have been traced in detail from Alabama to the Gulf of St. Lawrence and the events that led to the formation of the rocks described above have been interpreted as follows.

Sedimentation in Advancing Seas.—In late pre-Cambrian time a long period of erosion was followed by the beginning of the down-warping

of the Appalachian Trough. As the area warped downward it came to be occupied by the major stream of the region, the minor streams coming from the sides, so that sediments from a very large area came into it. At some period the ends were warped low enough so that the seas began to advance into the Trough and as they advanced they were furnished quantities of sediments by the great river that occupied the trough, and their waves reworked the alluvial fans and flood-plain deposits that were already there. In the shallow waters near shore, waves worked down to the solid rock; if the wave work was sufficiently vigorous sand and clay were carried away and pebbles and larger pieces of rock were left on the bottom. As the seas advanced farther and the pebbles that had been deposited were in deeper water, sand was deposited over the pebbles. Later, when the seas had advanced so that the shore line was hundreds of miles away and the sea was deep enough so that the storm waves did not strike the bottom, clays were deposited over the sands. In still later stages, with failure of even the finest of sediments to reach the region, limestones were deposited over the shales.

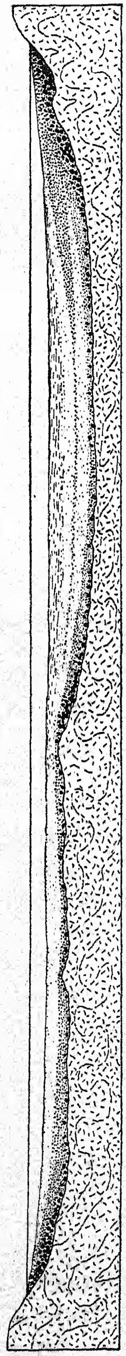

FIG. 338.—The sea spread westward from the area shown in Fig. 337 and the area of sedimentation increased in size. The conglomerates and sands at the left are younger than those in the bottom of the original trough and in the original trough sands and clays are being deposited at the same time as the pebbles and sands in the area newly covered by the sea.

Alternation of Sediments.—We might say that in a normal section of rock formed in an advancing sea there should be conglomerates below, succeeded by sandstone, then by shales, and finally by limestones. But such a succession rarely, if ever, occurs, for the progress of the sea is not uniform and during the general advance there are minor retreats. Stream flow varies greatly, stages of low water are succeeded by floods, and the entering streams carrying sediments change their courses. All of this has been treated in the chapter on the Work of Running Water, but we may consider a concrete example in this oldest Paleozoic sea. The shore line had advanced far enough that sands were being deposited over the pebbles when a great storm with very strong waves rolled pebbles out over the sand and sand was again deposited here as soon as the storm subsided. The shore line kept moving away from this place but after a few years another great storm again brought pebbles. This time, as the shore line was farther away, the pebbles were smaller. The lower rocks formed in an advancing sea, instead of

consisting then entirely of pebbles, are likely to be made up of alternating beds of sand and pebbles.

The same kind of variation took place when clays began to be deposited above sands in this area. Clays had been laid down to a thickness of 2 or 3 feet when a particularly great flood of some river entering the sea brought in much more sand with a much stronger current than usual, and a few inches of sand were deposited above the clay. After the flood, when normal conditions returned, clay was again deposited above the sand. Years later an unusually great storm stirred up the bottom farther out than usual and moved sand beyond the ordinary limit, so that sand again temporarily succeeded clay. Finally, when the shore line was far enough away, limes formed above the shales and continued to form for a long period.

Once a great river changed its course and entered the sea much nearer the place where the lime was being deposited. It carried a great deal of sediment and clay was again deposited above the lime, until the effect of the river was nullified by the shore moving too far away from the limestone region for clays to reach that place.

The above is merely showing possibilities. The unusual storms and unusual floods may come in periods of a few years to a few thousand years, while the change in the river would be much less frequent. The change of the Hwang Ho River as discussed on page 115 is an example of this. Alternation of different kinds of sediments is the expected thing rather than the exception in all changes from one type of sediment to another.

To go back to these first deposits on the pre-Paleozoic rocks that were formed by the sea advancing in the geosyncline, we find that the lowest deposits were alternating conglomerates and sandstones, followed by sandstones, followed by alternating shales and sandstones, then by shales, then by alternating limestones and shales, and finally by limestone.

But even this succession is very much generalized and ideal rather than actual, as in some places the sedimentation did not go beyond the sandstone stage and in others it did not reach the limestone stage before changes came that altered the entire order of deposition. In Fig. 339 assume that the point designated as 1 is a place where sand was being deposited near shore. The sea advanced up the trough so that the margin was finally hundreds of miles from 1 but the lateral margin of the sea stayed near this spot and sands were carried out to it as long as the sea remained over the area, or until the near-lying land was cut so low that it no longer furnished sand. Point 2 was far enough from shore to receive the normal succession, and while at point 1 sandstones formed all of the time after the first conglomerates, at 2 sandstones were succeeded by shales and shales in turn by limestones.

The limestones and shales at 2 might be of the same age as sandstones at 1. How then could the geologist, by examining a section at 1 and a section at 2 where a stream had cut through, as represented in Fig. 339*b*, determine the relative age of the rocks in the two places?

Use of Fossils.—Suppose that while the first sandstone was forming at 1 animals lived that we may designate by the letters A, B, C, D, E,

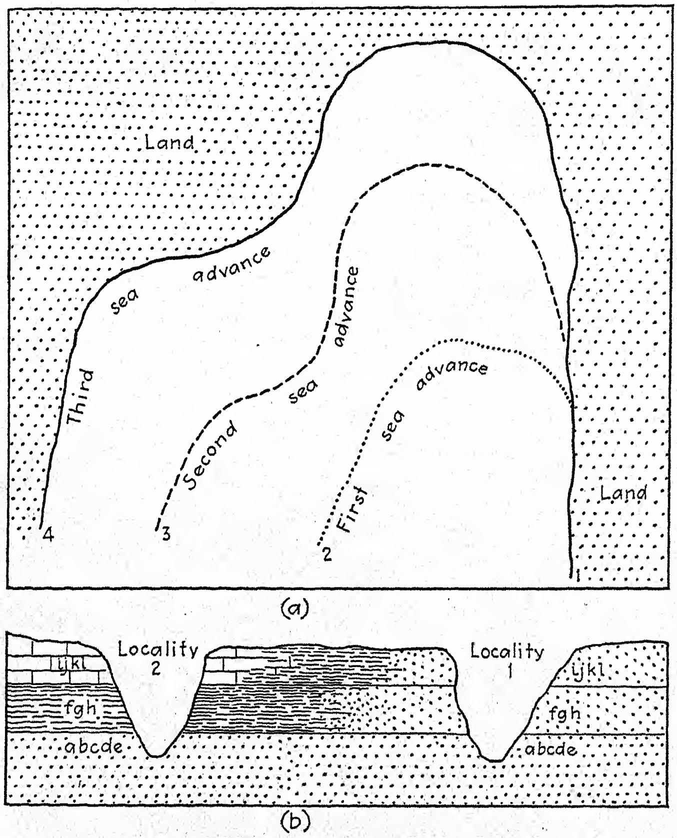

FIG. 339.—(*a*) Map showing conditions of sedimentation during part of the sea advance through the Appalachian Trough. (*b*) Section to show relationships of rocks and life near localities 1 and 2 of *a*. Just off the shore of 1 the deposits are all sand and pebbles. At 2 sands gave place to clays and clays to lime as the seas advanced and deepened.

and the same species lived in the sea at 2, but by the time the sea had advanced to 3 shales were forming at 2, life had changed very decidedly, and species may be called F, G, H. This would be true not only at locality 2 where shale was being laid down but at the sandstone locality 1 and in all of the sea of that time in the Trough. When the seas had advanced to 4, limestones became the dominant rock at 2, and life had again changed so that the main forms were I, J, K, L. This would be true also of 1 where sandstone was still forming and the relative ages of

the rocks could be readily determined by their fossils although the kind of rock would have no significance.

Source of Sediments.—The sediments that were deposited in the Trough were all derived from igneous and metamorphic rock. The metamorphic rocks were mainly gneisses, schists, and slates, and the igneous rocks were granites, basalts, diorites, gabbros, and felsites. The weathering of these old rocks appears to have been rather complete as much of the sediments was sands, clays, and limes.

Further Spread of Cambrian Seas.—The margins of these oldest Paleozoic rocks are on the eastern and western sides of the Appalachian Mountains and it is inferred from this that the seas in eastern North America occupied only the Appalachian Trough during most of the oldest period of the Paleozoic. However, there were many minor oscillations in the trough and the seas even withdrew almost completely during one part of the Cambrian. Before the close of this period the lands west of the trough became so low that the seas spread over them and a sandstone was deposited over wide areas in the central part of North America. The seas finally spread westward through the interior and the Rocky Mountain region and joined with another great geosynclinal sea near the Pacific (see upper Cambrian sea margins on Fig. 336).

The Cordilleran Geosyncline.—At about the same time that the Appalachian Geosyncline was forming, an even larger syncline formed, roughly parallel to the Pacific Coast, from the Arctic Ocean to near the Gulf of Lower California. The history of this syncline during the first period of the Paleozoic was much the same as that of the Appalachian Geosyncline, although the sediments deposited were thicker and more nearly continuous than in the east. At nearly the same time that the seas spread westward from the Appalachian region they spread eastward from the western geosyncline and they finally covered nearly half of the North American continent. In the early stages of this widespread sea the sediments were mainly sands and clays, but in the later stages so little land was exposed that only a small amount of sediments came into the seas and the deposits were mainly limestones.

The Close of the Cambrian.—The earliest Paleozoic period represents a time of little movement of the continental masses. After the seas had remained over the continent for perhaps 40,000,000 or 50,000,000 years they withdrew from the western area, the Appalachian Trough, and the interior, leaving only minor epicontinental seas on the land. This withdrawal constituted the close of the period. There was no mountain making of importance and no igneous activity.

ORDOVICIAN PERIOD

During the second period of the Paleozoic the seas advanced again through the Appalachian Trough as in their first invasion of the continent,

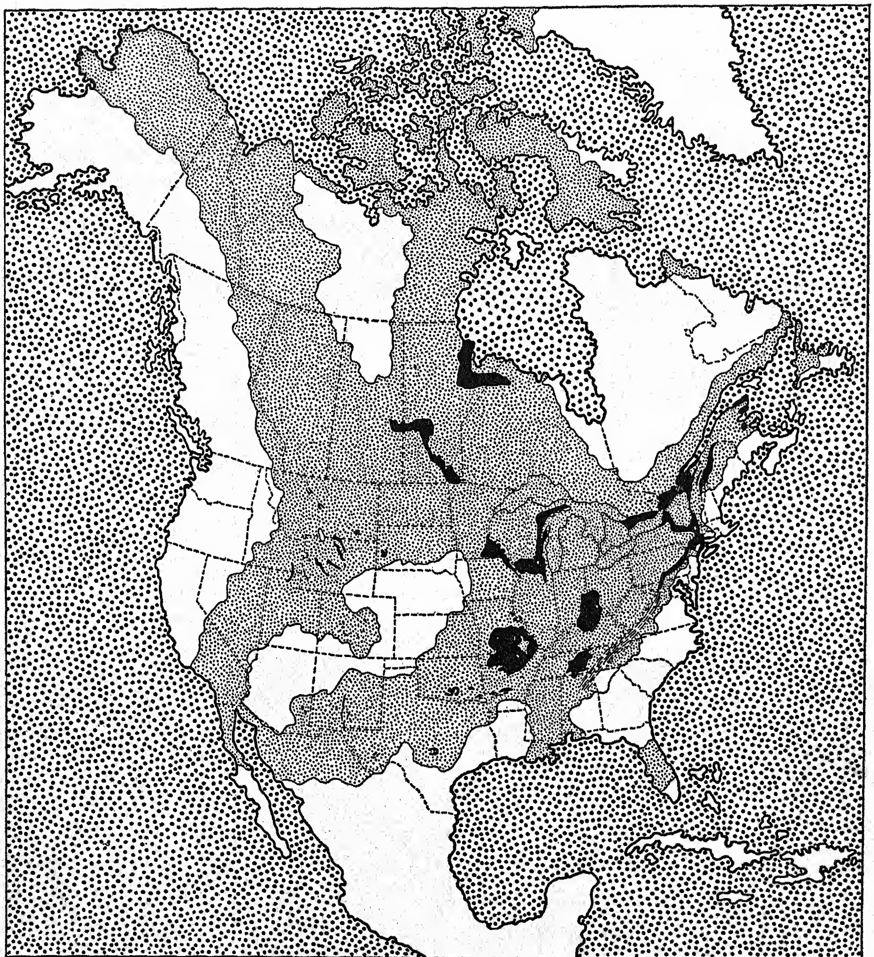

FIG. 340.—Ordovician seas and outcrops. Fine stipple represents middle Ordovician epicontinental seas. Black represents Ordovician outcrops. (*Seas modified from Schuchert.*)

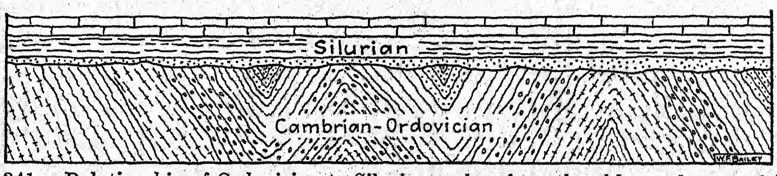

FIG. 341.—Relationship of Ordovician to Silurian rocks where the older rocks were folded and peneplaned before the Silurian sea advanced.

but they soon spread with many minor oscillations into the interior and to the Cordilleran Trough. Finally they covered about 60 per cent of the continent, constituting the widest spread of the continental seas during geologic time. At their maximum extent they were still oscillatory and retreated widely only to advance again over about the same area. The period closed with a widespread withdrawal and with extensive mountain folding in western New England and eastern New York, usually designated as the Taconic uplift. The time of the formation of the mountains is fixed, because rocks of the second period are greatly folded and eroded and the rocks of the next period were deposited horizontally over the tilted beds (Fig. 341).

LIFE OF THE CAMBRIAN

Records of life before the Paleozoic are very scarce, although as stated in a previous paragraph several different kinds of animals are known from their fossils. The rocks of the first Paleozoic period are sometimes characterized as the oldest rocks bearing fossils in abundance. As the seas came into the Appalachian Trough and the Cordilleran Trough they brought with them many kinds of animals which had developed between the time of the youngest known pre-Paleozoic rocks and the oldest Paleozoic. The life that came in was nothing like the life of the present. Probably the most striking absentees were the animals that now dominate the earth, the vertebrates or backboned animals. This is the group to which the fishes, crocodiles, birds, horses, elephants, man and nearly all of the large animals belong. Notwithstanding the absence of the vertebrates, the animals as a whole were well on their way toward the highest organization. Probably nine-tenths of all significant structures in animals had already appeared at the time of the beginning of the Paleozoic period.

Trilobites and Brachiopods.—Two types of animals that were of great importance throughout most of the Paleozoic, and of which we therefore need to learn a little, dominated the oldest Paleozoic seas. These were the trilobites and the brachiopods, of which pictures are shown on Plate 342. The trilobites were remotely related to the modern lobsters and crawfishes. The brachiopods had their bodies covered with two shells and roughly resembled clams, although not closely related to them. More than 90 per cent of the animals in the first Paleozoic sea were brachiopods and trilobites; if you should find a rock in which brachiopods and trilobites are the main fossils and other types are rare or absent, you might identify this piece of rock as having come from the oldest Paleozoic period with a considerable degree of confidence, but not with certainty.

No Vertebrates or Voracious Animals.—In the rocks of the Cambrian period not a single bone has been found, and if animals with bones were present geologists would almost certainly have discovered their remains.

Fig. 342.—A restoration of brachiopods and trilobites in a Cambrian sea.

This is the only period in geologic history when there were no voracious animals, no animals to feed upon one another. There were animals that strained out the minute forms of life from the water and used them as food, but there were none that could seize other animals and devour them.

Lower Paleozoic Stage of Development.—Although evolution was so well along, the life forms were young and almost all of the main ones were still to be evolved. One of the laws of evolution which is probably invariable is that youthful forms change rapidly whereas old-age forms change slowly. No old-age form seems ever to have given rise to anything radically different from itself. The Cambrian forms were youthful and changes went on rapidly. With the first seas there seem to have come in not more than 10 species of trilobites; more than 400 species had appeared before the close of the period. On an average each species produced 40 new ones. You may visualize this by imagining 40 kinds of birds, such as crows, hawks, ducks, geese, and sparrows, developing from some well known bird.

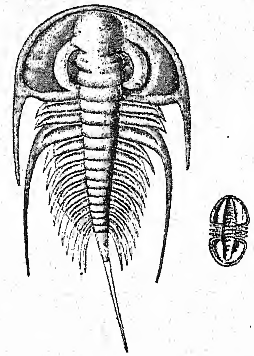

Fig. 343.—Cambrian trilobites. (*After Walcott.*)

It might be assumed that this is very rapid evolution, but the matter deserves a little further consideration. How long was this oldest period? If we say 50,000,000 years the evolution takes on quite a different aspect and the changes may have been very slow, imperceptible through periods many times as long as historical time.

We may trace the evolution of one species into the many that it produced by studying Fig. 345. One species came in with the first seas of the period and minute changes gradually accumulated until the original species was no longer recognizable, but two species, both slightly different from the original and slightly different from each other, had arisen. At this stage, at the end of 10,000,000 years, three species had existed. In the next 10,000,000 years each of the two new species formed two others, so that four species were living at the end of 20,000,000 years and three had died out. In the next 10,000,000 years each of the four gave rise to two more, so that at the end of 30,000,000 years eight species were living and seven had died out. At this rate of evolution 63 species would have evolved in 50,000,000 years, of which 32 species would be

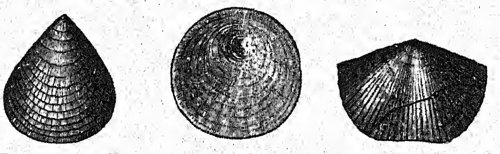

Fig. 344.—Cambrian brachiopods. (*After Walcott.*)

living and 31 would have died out. You will recognize that no such regularity of evolution or of results could be expected or would ever occur, that accident plays a very large part in evolution, and that some species might give rise to many while others gave rise to none. The emphasis here is on the slowness of the process.

Students unfamiliar with the various proofs of the length of geologic time are likely to think that investigators on living animals should be able to notice permanent evolutional changes, but the geologist does not consider that likely, as all changes that he has been able to trace in the geologic past have been exceedingly slow in terms of historical time.

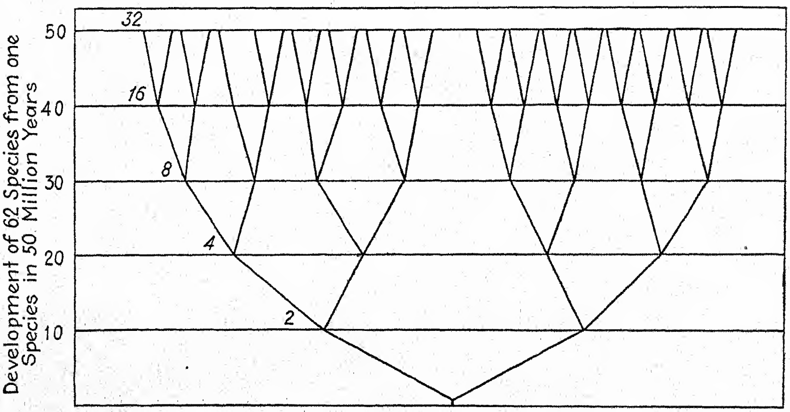

FIG. 345.—Development of 62 species from 1 species. The diagram represents possible results from slow changes—the development of two species from one in 10,000,000 years.

Effects of Change of Environment.—The youthful forms coming into the early Paleozoic seas had other factors than youth in favor of rapid evolution. As the seas spread over the continents they gave opportunity for rapid changes in environment. The animals had been living in shallow water near the shore and the spreading seas may have forced them into deeper or shallower water, muddier or clear water, fresh or brackish water, still or agitated water, colder or warmer water. Any one of these changes might favor some particular modification of the animal and hasten the evolution in that direction or it might destroy the animal. The spreading of the seas at any time or even the shrinking of the seas forces modification of habitat and consequently favors certain characteristics of the animal at the expense of others.

The seas withdrawing at the close of the first period probably exterminated many species which had become accustomed to certain living conditions and could not adjust themselves rapidly enough to the new ones forced upon them. A graphic example may serve to illustrate this. Suppose that the waters should begin to rise on the North American continent until all lands lower than 8,000 feet were submerged. You

may well imagine what would happen to many species of animals now living on the continent. The land above 8,000 feet high is all in the Rocky Mountain region and the high mountains near the Pacific Coast. All of the land animals would be forced into an area no larger than the state of California. That area could not produce enough food for the 120,000,000 people of North America, and unless food could be brought in from the outside the human population would have to decrease. Those species of animals that could not be used for food probably would be exterminated and those species of plants that were not in some way directly useful to man would be killed off. In the process of change it is not infrequently the case that animals adopt a new habitat as distinctly different as air from water. This would be a particularly favorable time for such adjustment and it would be likely that some species would adapt themselves to living in the seas. No rapid adjustments would be required but very great changes would be necessary before the adaptations were complete, and the animals' regular habitat became water.

Absence of Land Life.—No land life of the earliest Paleozoic period is known. If such were present it did not leave fossils in the rock. With no plants or animals the land was just barren rock. There was no protection from geologic processes by a covering of plants and the details of erosion must have been somewhat different then than now.

LIFE OF THE ORDOVICIAN

The second period which is the upper part of our Lower Paleozoic had forms of life decidedly different from those in the first period. The

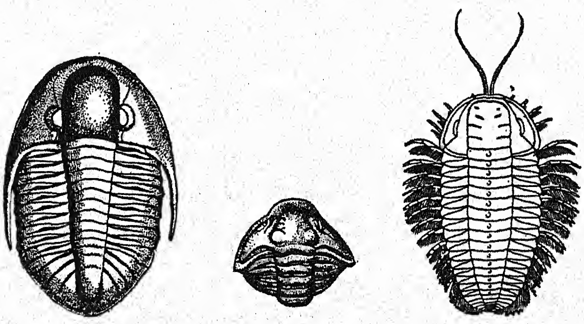

FIG. 346.—Ordovician trilobites. *(After Goldring, courtesy of New York State Museum.)*

restricting sea had caused great modifications and the disappearance of great numbers of species. The readvance of the sea gave opportunity for remaining forms to develop and expand and for new species to originate. Not only did new species in great numbers come in, probably 4,000 or 5,000 being known from the second period, but not more than 10 or 15 of the more than 1,000 species of the Cambrian lived over into Ordovician. Entire new groups of animals appeared and some of these

took the place of dominance that was held in the first period by brachiopods and trilobites.

Cephalopods.—We need pay attention to only two of these groups. One of them is the cephalopods, of which the pearly nautilus and the devilfish are modern representatives. The group was represented only by small and inconspicuous individuals in the first part of the period, but in the second part they became the largest and most powerful of the earth's inhabitants. The first of these had small cone-like shells, and as they developed the cone increased in length and became a long, slender, straight shell. With the growth of the individual it added to the length of the shell and left the older part unoccupied. This was accomplished by the addition of a cross partition behind the animal each time it moved forward. Some such shells, more than 1 foot in diameter and 12 or 14 feet long, have been found; but with the very beginning of the evolution of this form, before the close of the second period of the Paleozoic, it assumed a great variety of forms. The straight shells were the most common but some were slightly curved, strongly curved, or loosely coiled, and still others were tightly coiled. All had partitions in the shell and the entire group may be recognized by these partitions. If it were not for the partitions many of the shells would greatly resemble those of snails.

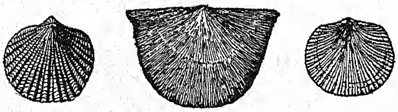

FIG. 347.—Ordovician brachiopods. (*From Paleontology of New York.*)

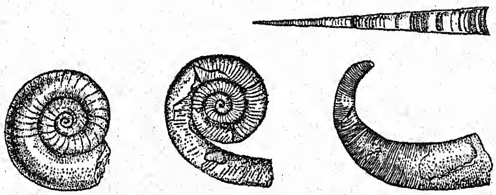

FIG. 348.—Ordovician cephalopods, about 1/10 natural size. (*After Goldring, courtesy of New York State Museum.*)

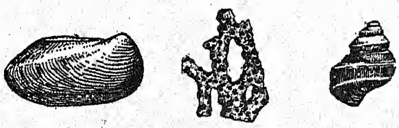

FIG. 349.—Ordovician clam on the left, bryozoan in the middle, and snail on the right, about ½ natural size. (*After Goldring, courtesy of New York State Museum.*)

ORDOVICIAN

Fishes.—The other important group that appeared was the fishes, the first of the vertebrates. This was a great advance in life and made possible many changes advantageous to animals, changes that could not evolve under the old system. The old forms that possessed hard skeletons had them on the outside of the body as shells. The forms like the modern crawfish and grasshopper, represented in the early Paleozoic by the trilobites, periodically break open the outer covering, escape from

it and form a new covering. This was highly wasteful and comparable to a man having to burn down his old house before he could have a new one. The development of the internal skeleton allowed complete freedom of change and the evolution of the highest types of animals.

Absence of Land Life.—No fossils of land animals or plants have been found. There can be no doubt that the more primitive plants lived in great numbers, as animals depend indirectly at least upon plants for their food. No animal has the power within itself of taking chemicals directly from the air, the water, or the rocks and transforming them into animal food. Plants perform this function and animals must either eat the plants or eat other animals. Most certainly the first living matter to

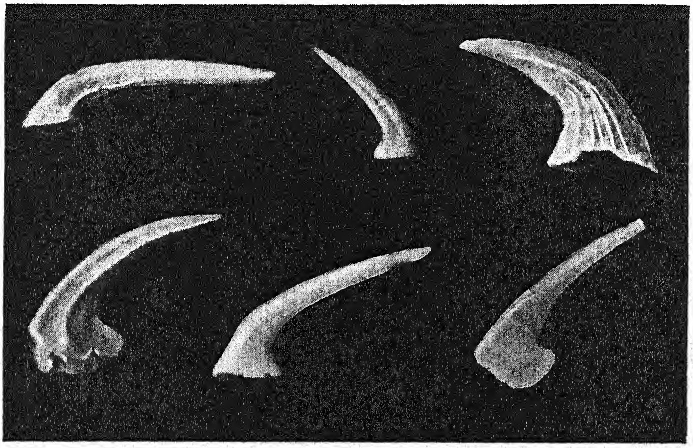

FIG. 350.—Ordovician fish teeth. Six species selected from lower Ordovician fishes known as conodonts. All enlarged 25 diameters. (*From Branson and Mehl.*)

originate was the lowest type of plants. Although trilobites and brachiopods no longer dominated the life of the seas, both were considerably more abundant than they had been in the first period. It was an increase in the other types of life rather than the decrease of these forms that ended their dominance. The difference between the fossils in a piece of rock of the first period and one of the second period each containing typical animals is that the first would have almost all brachiopods and trilobites while the second would have brachiopods, cephalopods, and several other animal types. You should not, however, expect to find fishes in the rocks of the second period. Probably not one geologist in a hundred has ever collected any fish remains from the second period.

ECONOMIC PRODUCTS

Cambrian.—The economic products from the Cambrian are not of great importance. Some of the gold from the Black Hills is in the sandstones and conglomerates which were formed at the time of the very

widespread sea near the close of the period. The gold was a placer deposit with the conglomerate. Such placer deposits are formed by the weathering of gold veins and streams transporting the pebbles of rock and flakes of gold and redepositing them. Gold is very heavy, about six or seven times as heavy as ordinary rock, and is segregated because of this in gravel. A considerable amount of the gold mined in the world is recovered merely by washing gravel. When such gravel formed in one of the older rocks and the sediments became consolidated, it constituted a consolidated placer. This is the type of placer mined in the Black Hills. Such Cambrian placers are not uncommon but the Black Hills seems to be the only place where they are mined; even there they do not constitute the main source of the gold. The greatest lead deposits in the United States are in Cambrian rock in southeast Missouri, in a limestone formed at the time of the greatest extent of the first-period sea. The lead particles are disseminated through the limestone and were deposited there subsequent to the time of formation of the limestone, probably by warm or hot water moving upward through the rock and carrying the lead in solution. The ore mineral is galena, which consists of lead and sulfur. The lead ore was one of the reasons for the early exploration and early settlements of southeast Missouri. However, the French were hunting for silver and mined the lead only incidentally. The oldest mines in the Mississippi Valley were in this region and date back to 1720. For many years this region produced more lead than any other in the world and there is no indication that the ore bodies are near exhaustion.

Ordovician.—The Ordovician economic products are considerably more important than the Cambrian, and oil and gas have constituted one of the most important of the products. That most widespread limestone that formed in the sea that covered about 60 per cent of the North American continent, a limestone widely known to oil men as the Trenton, contained the oil of the western Ohio–eastern Indiana field, which is developed on the top of a low anticline known as the Cincinnati Arch. This was one of the early fields of importance, now nearly exhausted. At one time it produced some 20,000,000 barrels of oil per year and its production at present is less than 500,000 barrels per year. Up to about 1912 this was the only area that had produced oil in paying quantities from the Ordovician, but since that time such occurrences have been found in Kentucky, southern Illinois, and particularly in Oklahoma. In Oklahoma nearly all the deeper wells get their supplies from the Ordovician and the rock is producing more than even the younger rocks of the area produced in the early days of the Oklahoma fields.

Lead and zinc from Illinois, Iowa, and Wisconsin come from the Ordovician rocks.

A formation called the St. Peter sandstone is one of the main artesian water bearers of the northern Mississippi Valley, and artesian water is one of the most important of the economic products. The sandstone is noted for the lack of impurities in its grains and cementing material and because of its purity is used extensively for the manufacture of glass.

CHAPTER XIX

PETROLEUM GEOLOGY

The Anticlinal Theory.—Among the numerous contributions made by geologists to the economic conditions of the times probably none has been more important than the application of geological principles to the discovery of petroleum fields. As late as the first decade of the twentieth century the discovery of petroleum "pools" was largely a matter of

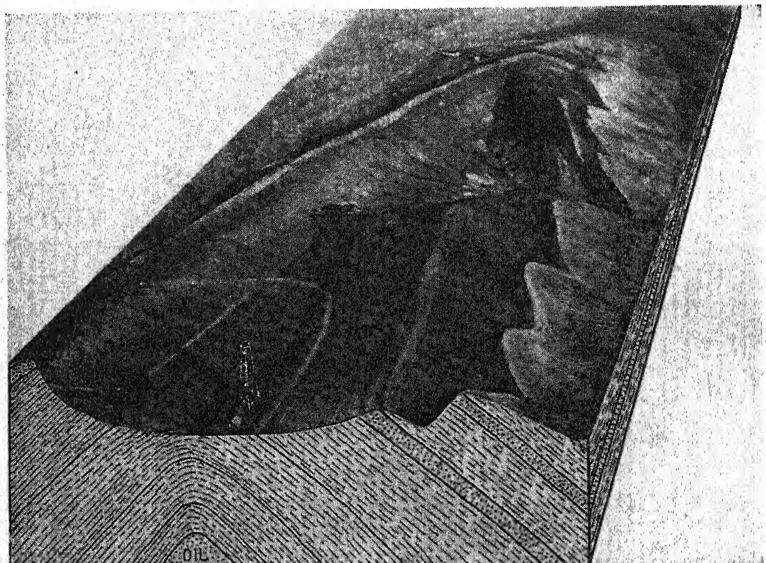

FIG. 351.—Photograph and section of part of an oil-bearing anticline. The rocks at the right dip to the east, the rocks in the distance dip to the north, and the rocks at the left dip to the south. This is the north end of a long narrow anticline. (*Photograph by Willard Bailey.*)

guesswork. The earliest petroleum fields developed in the United States were in West Virginia, Ohio, and Pennsylvania. Dr. I. C. White of the West Virginia Geological Survey observed that wells drilled on the tops of anticlines yielded more petroleum than those drilled at other places. For several years he checked his observations and finally formulated from them the *anticlinal theory*—a formulation that merely goes back to his first observation that petroleum is found mainly in the tops of anticlines.

At the present time geologists, the world over, in their search for new bodies of petroleum select anticlines as the most likely locations. This

does not mean that they look for the tops of hills. Your study of anticlines has shown you that the tops of anticlines may be in the bottoms of valleys (Fig. 351) or may be on the tops of hills. If you will refer to Fig. 352, you will note that the stream in this case flows through the top of

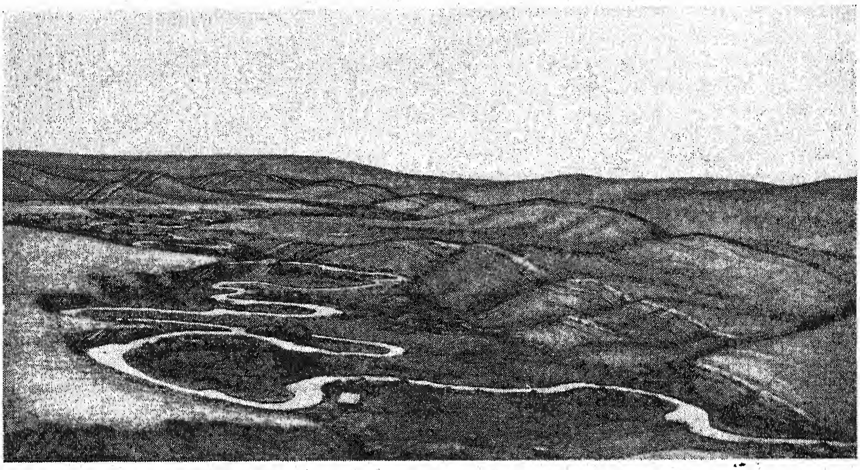

Fig. 352.—A stream valley in the top of an anticline. The beds on one side of the valley dip to the right, on the other side, to the left. (*Photograph by E. B. Branson.*)

the anticline. The wells are drilled in the bottom of the valley. Figure 353 of another oil field in the same vicinity has the wells drilled in the top of the hill but nevertheless at the summit of the anticline. It is a rather

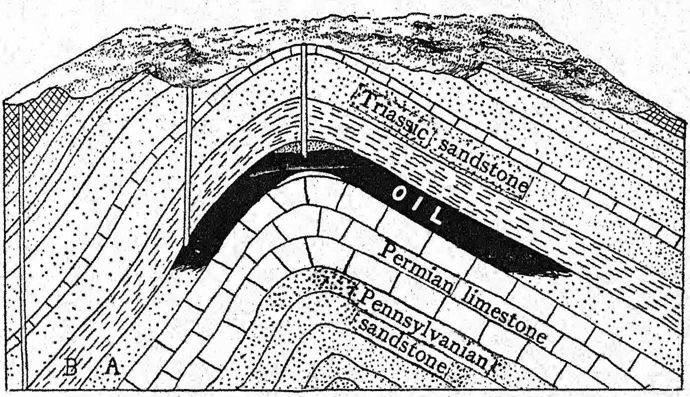

Fig. 353.—An oil-producing anticline in Wyoming showing two producing wells and a dry hole. (*A*) An oil sand; (*B*) a shale that forms an impervious cap to the oil sand.

common thing for fake geologists to go into a region and recommend drilling on the tops of hills.

When a geologist starts to investigate an area where he is unfamiliar with the geology and can find nothing published to give him real information about such geology he first works out the geologic section, *i.e.*, he finds out the age and kind of the surface rock and of all the rocks as far

down in the section as he can get at them. From your study of rocks in the field you have discovered that if the strata are turned up on edge or steeply dipping as shown in Fig. 354 you can measure a thick section without having deep valleys or high hills.

It may be worth while to follow a geologist in his actual work of finding out the section. He goes into the field shown in Fig. 352. He has no difficulty in seeing that there is an anticline at this place but it may be possible that igneous rocks are near the surface or that there are no rocks suitable for petroleum production within reach of the drill from

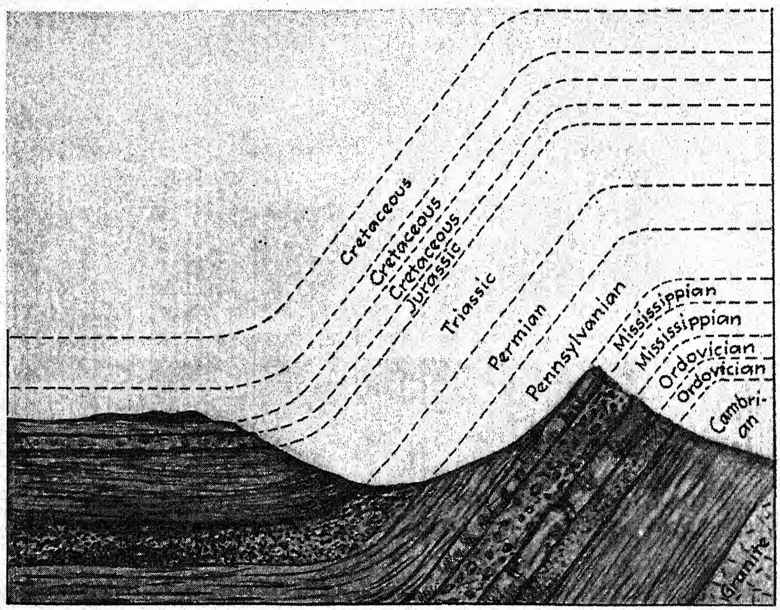

FIG. 354.—A geologic section from pre-Cambrian granite to Mesozoic rocks, as they are exposed 10 miles south of the area shown in Fig. 353.

the top of the anticline. About 10 miles south of the anticline a stream cuts through the mountains and exposes a full section from granite to the surface rocks of the anticline. The red rocks at the surface of the anticline are nonfossiliferous sandstones which are not likely to yield oil. Below about 700 feet of the red sandstone is a sandy shale and thin-bedded limestone; below this in turn are rather coarse-grained sandstones, and interbedded with them are highly fossiliferous limestones. The animals that are represented by the fossils may have yielded petroleum on their partial decay and the petroleum may then have migrated into the sandstone and saturated it. The sandy shales above the sandstone would prevent the petroleum from going higher.

The geologist pays particular attention to the age of the rocks in certain fields. Some fields produce from rock of only one age, as in the

field shown in Fig. 353. Others may produce from rocks of several periods, as in Pennsylvania and Oklahoma.

The most important Paleozoic oil fields in the United States are those of Oklahoma, Texas, and Kansas, which produce about one-third of the total output of the United States, some 280,000,000 barrels per year. Up to a few years ago all of the oil of these fields came from the Pennsylvanian rocks, the next to the youngest of the Paleozoic. Drillers declined to drill below the Pennsylvanian rocks. When some of the best fields neared exhaustion wells were deepened to Ordovician rocks, which were found to be even more productive than the higher beds, and at the present time wells in nearly every producing field in Kansas and Oklahoma are being drilled to the older rocks.

A Producing Anticline.—Figure 353 illustrates several phases of geology of petroleum. Well No. 1 is located directly in the top of the anticline and can most advantageously drain the entire anticlinal structure. However, in some large oil fields the well would be poorly located as gas accumulates above the oil and this well might be a heavy producer of gas but produce no oil. In that case the next well would be drilled at location 2 so as to strike below the gas and get the oil. One well was drilled at location 3 and the drill struck the producing sand at 3,000 feet but got nothing but water. In this field, as in many others drilled without accurate geological information, drilling off-structure has used up all the profits.

Age of Oil-bearing Strata.—If the geologist making the investigation had found that the rocks immediately underlying the surface rocks in Fig. 352 were Cambrian in age he would have paid no more attention to the field, as rocks of that age have been found productive in only one place in the world. Geologists would not say that Cambrian rocks may not be found productive but merely that their experience has shown that it isn't worth while spending money attempting to get petroleum from rocks that old. If it had been found that the rocks immediately underlying the red rocks were granite or other igneous rock, negative conditions for oil would have been still further emphasized and geologists would have said its occurrence was impossible. In a recent test for oil in one of the central states of the United States granite was struck and drilling was continued with the hope of passing through the granite to find other sedimentary rocks below. The fallacy is evident to anyone who understands how granites are formed.

Paleozoic oil of importance is now being produced in Oklahoma, Kansas, West Virginia, Pennsylvania, Arkansas, southwestern Texas, Kentucky, Illinois, and Indiana.

More than half of the petroleum of the world is produced in the United States. This does not mean that the United States actually has in reserve half of the petroleum of the world but rather that it is using

up its supply faster than the other countries. New fields are discovered every year, but that must come to an end, probably during the first half of the twentieth century. When new fields cease to be found, petroleum production will decrease rather rapidly, and either a substitute must be found for gasoline or the use of gasoline-driven machinery must decrease and the United States must come to the condition of some other countries where gasoline is very high in price. At present petroleum is being produced without great waste. This has come about by improvement in methods by the oil companies and improvement in laws of production by the various producing states.

Natural gas is probably the cheapest and best fuel extant; it is generally produced with petroleum, though there are some gas fields that produce no petroleum and some petroleum fields that produce no gas. In the earlier days of petroleum and gas production it was not uncommon to drill in a gas well and allow the gas to escape into the air. In that way great amounts of this high-grade fuel were wasted. Most states now have laws that prohibit such waste, and all gas wells must be capped so as to conserve the gas in the ground. Gas may be piped for long distances to market, but there are large wells in remote places from which no gas is being used. Near Farmington, New Mexico, are two wells, one capable of supplying about 85,000,000 cubic feet per day and the other about 70,000,000 cubic feet per day; both are capped, no gas being used from the field. No doubt this field would furnish many other wells of similar capacity if it were drilled. Where the wells are so far from places of consumption the cost of the gas is greater than the cost of other fuel.

Petroleum and natural gas occur in strata younger than Paleozoic and will be mentioned in later paragraphs.

ORIGIN OF PETROLEUM

The way in which petroleum originated was for a long time in controversy and even at present there is not entire agreement among investigators, although almost without exception geologists believe that it came from plants and animals that lived in the seas at the time that the sediments were forming. The evidences that go to prove this are numerous. First, no large bodies of petroleum have ever been found unassociated with sedimentary rocks. Second, rocks that are not associated with abundant fossils, either directly or indirectly or through porous rocks so that the oil might migrate to them, do not contain large amounts of petroleum. Third, petroleum can be formed in the laboratory from the fatty materials of plants and animals.

It seems probable that when the sediments were being deposited the animals and plants living in the seas formed petroleum by partial decay of their fatty tissues. In clear water the petroleum drops would rise to the surface and evaporate, as they are lighter than water; but in water

containing clay particles the drops might attach themselves to such particles and the particles carry them to the bottom where they would be buried in the muds. The mud might then come to be saturated with petroleum. The material resulting from the decay may have been some other form of hydrocarbon rather than petroleum and have been changed to petroleum later in its history.

Petroleum may be manufactured in the chemical laboratory from iron compounds, but it occurs nowhere in nature in such situations as to suggest origin from iron and nowhere near to bodies of iron of quantity great enough to furnish the necessary materials. Petroleum produced from iron in the laboratory lacks certain properties that all natural petroleum possesses. Imagine, then, widespread shallow seas, depth ranging probably from 200 or 300 feet to 1,000 feet; animal and plant life abundant; sediments in the water sufficient to carry down the petroleum drops. Do not consider that the water was muddy, as in that case the animals and plants would not be present in abundance, and if they were the sediments would form so much faster than the oil droplets that the resulting muds would contain insignificant amounts of petroleum. You are scarcely aware of the dust in the atmosphere, but it is probably settling as fast as the sediments were settling in the seas at the time that the great amounts of petroleum were formed, possibly at the rate of 1 foot in 4,000 or 5,000 years, with 1 pint of petroleum per cubic foot of rock in the same length of time. From this you can imagine the rate of exhaustion of petroleum at the present time over the rate of formation, probably more than a thousand times as fast as it is being produced, possibly more than a million times. There is no way of making even an approximate estimate. However, it is a duty of all intelligent citizens to conserve such natural products in every way possible.

CHAPTER XX

MIDDLE PALEOZOIC

The periods that we shall consider as Middle Paleozoic are the Silurian and Devonian of the standard section. The Middle Paleozoic is strikingly different from the Lower in several respects. The periods are based on the sedimentary rocks laid down during a great advance of the sea as was the case in the Lower Paleozoic. In the third period, the Silurian, the seas were quite different from those of the other periods. The western margin of the sea was a little west of the Mississippi River, while in all the other periods far western regions had been under water. Most of the Rocky Mountain region is entirely free from Silurian deposits. The Devonian seas were not so extensive as those of some other periods but their rocks occur in both eastern and western areas and through the interior. In both periods the Appalachian Trough was one of the early places to be invaded and served as a depository through most of their duration. The rocks of both periods are shales, limestones, and sandstones, with limestones forming a larger proportion than would normally be expected, or than would be expected from the coarse materials derived from normal weathering. Two new kinds of rocks, salt and gypsum, are of importance in the Middle Paleozoic although not of very great extent. They occur in New York, Ohio, and Ontario.

The relationship and extent of the formations show that the seas oscillated a great deal and they did not in every case cover the same areas on readvancing. Salt and gypsum are present in the rocks of only a few periods; as the materials for them are very common, they should be present every place if they formed normally. Clearly they required some special condition for their formation. Late in the Silurian period the seas withdrew from most of the North American continent and isolated bodies of salt water were left in New York, Ohio, and Ontario. Most of these bodies of water were merely shut off by bars from larger bodies of salt water. The climate must have been arid so as to make evaporation equal or exceed the inflow from streams. Apparently many of the isolated bodies of water completely evaporated and all of the salt and gypsum was precipitated on the sea floor. The sea water contains about 1 part in 100 by volume of salt. As some of the salt deposits are 200 feet thick, more than 20,000 feet of water must have evaporated in order to deposit that much. However, one should not assume that there was a basin 20,000 feet deep for the water was comparatively shallow at all times.

LIFE OF MIDDLE PALEOZOIC

Trilobites.—The life of the Middle Paleozoic in its general aspects was not very different than that of the Lower Paleozoic. In the seas the trilobites, brachiopods, and cephalopods were dominant forms. Trilo-

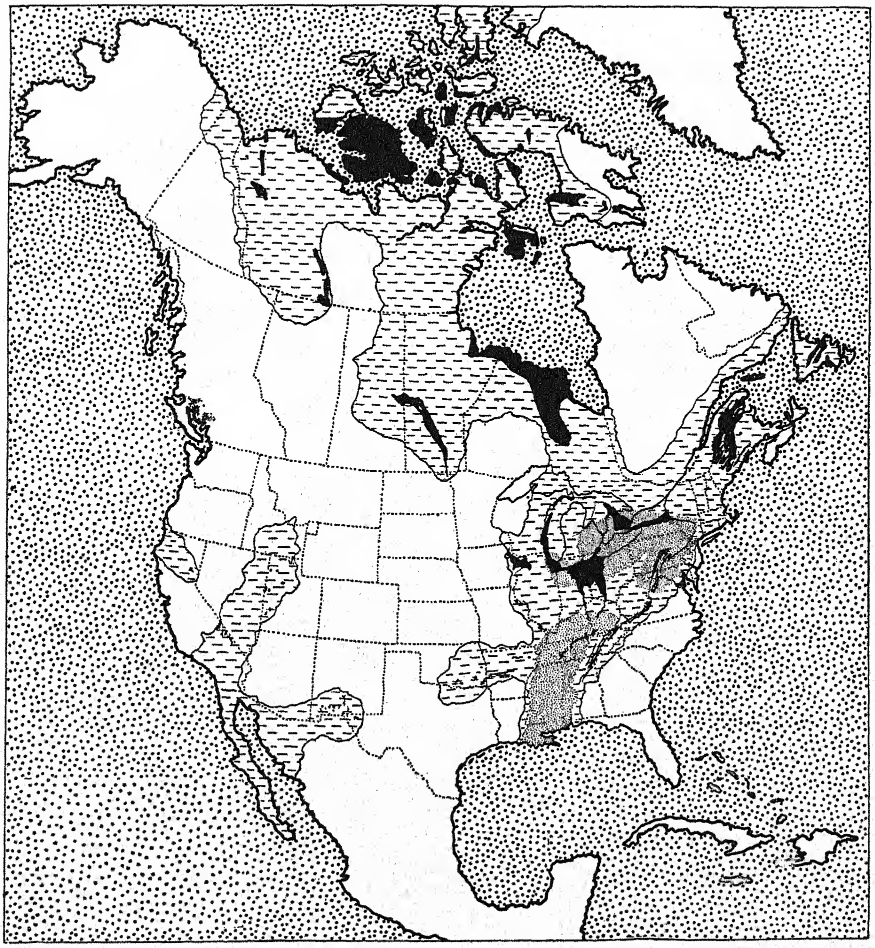

FIG. 355.—Silurian seas. (*Modified from Schuchert.*) Fine stipple represents areas of late Silurian epicontinental seas. Dashes represent areas of middle Silurian seas. Black represents outcrops.

bites were showing old-age characters before the close of the Devonian. In the earlier Paleozoic they had been young and subject to great numbers of variations. In the Silurian they became less and less varied and in the Devonian the old-age characters showed plainly.

Old Age Characteristics.—Of life in general it may be said that one of the most conspicuous marks of a group entering "old age" is the

development of useless structures commonly designated as "ornamentation." With the trilobites these were in the nature of spines and nodes

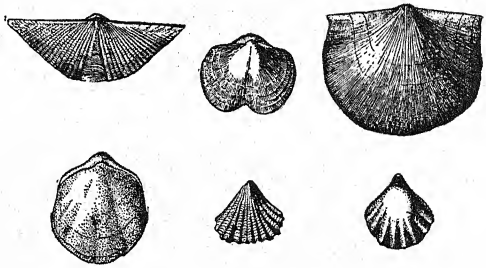

FIG. 356.—Devonian and Silurian brachiopods, about ½ natural size. (*From Paleontology of New York.*)

on various parts of the body. They had ceased to take on important changes and were not developing many new species. One familiar with the development of life in the geologic past might predict, after examining the Devonian trilobites, that they were at about the end of their course.

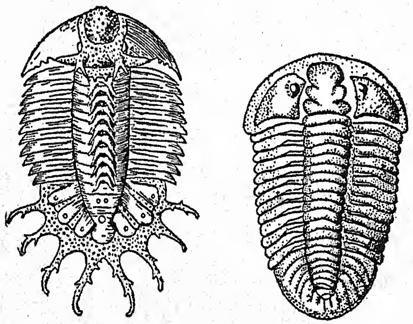

FIG. 357.—Devonian trilobite on the left, Silurian trilobite on the right. (*After Goldring, courtesy of New York State Museum.*)

Cephalopods.—Among the cephalopods a new type of structure appeared that was later to become the dominant feature of that group. The partitions in the shells had been simple gently curved plates up to this time, but here there appeared a form that had strong flexures in the edges of the partition, called lobes and saddles.

Fishes Develop Paired Fins.—Fishes, which had appeared in the second period, were rare and small in the third period. They came to the time of great evolutional vigor and great changes in the fourth period, the Devonian, which is known as the Age of Fishes. By the middle of the period they had branched out into four main lines of development. One of these was the sharks, which appeared here for the first time and which in some respects constituted a great advance among fishes. Some of these sharks show the development of paired limbs, which up to this time had not been present. The fish fins had been long folds of skin along the sides of the body. Now the bone supports of these folds became segregated into four groups, two on each side of the body, and folds of skin were restricted to the four groups of bone to form the paired limbs. Bony fishes, which are today

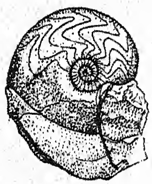

FIG. 358.—A Devonian cephalopod with complex sutures. (*From Paleontology of New York.*)

and have long been the dominant group, had their ancestral forms in the Devonian, but all of them were small and of little importance.

Armored Joint-neck Fishes.—One degenerate group, the "jointed necks," assumed some striking peculiarities and in some places became the dominant form of fishes and the largest in the Devonian. Almost all of their bones were different from those of other animals and few of the bones can be identified as present in other animals. One striking difference is that the lower jaw and the teeth of the lower jaw consist of just one unit. All the other fishes have several bones in the lower jaw and the teeth are separate pieces. They are called the joint-necked

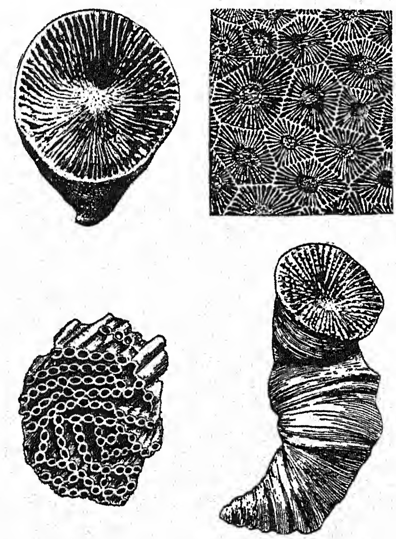

FIG. 359. FIG. 360.

FIG. 359.—Devonian and Silurian corals. (*From Pirsson and Schuchert, courtesy of John Wiley & Sons.*)

FIG. 360.—A Silurian crinoid showing head, stem, and roots, about ⅓ natural size. (*From Pirsson and Schuchert, courtesy of John Wiley & Sons.*)

fishes on account of a ball-and-socket joint between the skull and some armor plates on the back of the fish. These armor plates were a new type of development. On the middle of the back was a heavy shield-shaped piece of bone and on either side of this piece were other bony plates. Two of the latter, one on each side, articulated with the base of the skull by means of the ball-and-socket joint. Here was the first heavily armored animal that had come into existence and it furnishes us with another lesson in the economy of evolutionary development, which is that heavy armoring, though it may protect the animal temporarily, finally leads to extinction. Some of these fishes reached a length of 25 feet or more and may be considered as giants among all animals of that time. Although they developed only in middle Devonian most of them did not outlive the Devonian and all became extinct early in the next

period. This is our first record of extinction of an entire race. Another law of evolution is also illustrated here, that giantism leads to extinction. Very large animals belong to short-lived species; heavily armored species soon become extinct. These fishes are found mainly in the upper Devonian of Ohio and New York but some are known from various other regions. The black Devonian shales of northern Ohio are the best collecting ground for them.

Lung Fishes.—Another striking type of fish was one that developed lungs and was able to breath air and live on land. Those are known as

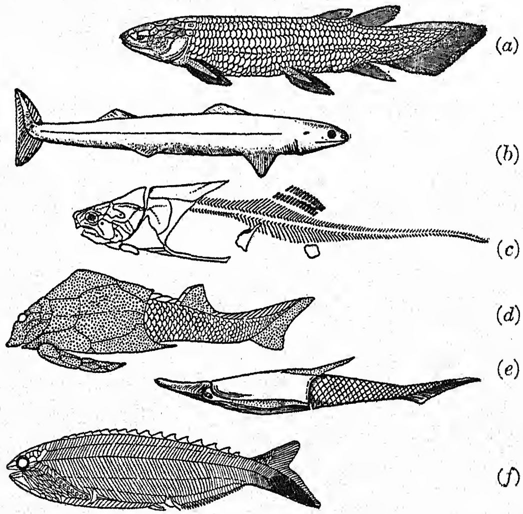

FIG. 361.—Some of the best known Devonian fishes. (*a*) Lung fish, (*b*) shark, (*c*) joint-neck armoured fish, (*d*) and (*e*) armoured fishes, (*f*) a late Silurian fish. (*a, b, c, d, e, from Pirsson and Schuchert, courtesy of John Wiley and Sons; f, after Kiaer.*)

the lung fishes and constitute the first record of a vertebrate that could live out of water. Their lungs were probably a mistake in development, as the gills were more efficient breathing agents than such lungs. These fishes developed another inefficient structure: the paired fins became elongated and changed into a sort of legs without feet, enabling the animal to move about clumsily over the earth's surface. Here were two unsuccessful types of evolution toward higher forms but the structures were not conducive to greater efficiency and the animal never progressed beyond the stage found in the Devonian. Although there are two or three species of lung fishes existing, their greatest abundance was in the Devonian. No other form seems to have developed from them and they are not to be confused with a very similar development to be mentioned presently.

Amphibia.—A principle of evolution emphasized in the chapter on the Lower Paleozoic is that at times of rapid evolution in young groups, when they are giving rise to a great variety of new forms some large

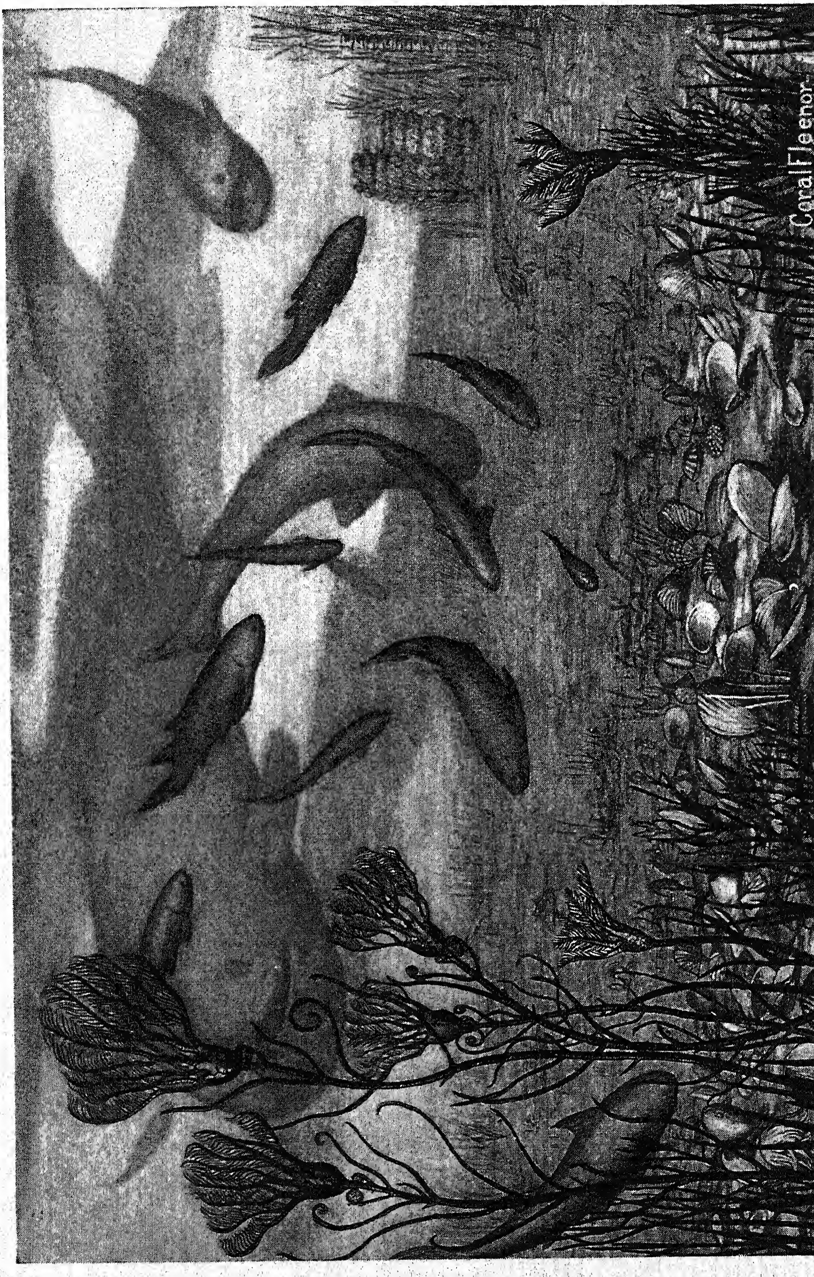

FIG. 362.—Restoration of Devonian sea life. A large armored fish in the background sharks and other fishes in the foreground; crinoids in the foreground; sponges in the right background; brachiopods, clams, and cephalopods on the sea floor.

change is likely to appear that develops into some radical upward trend in evolution. The fishes were evolving very quickly and producing great numbers of radically different types. They had developed paired fins (almost paired legs in the lung fishes) and they had developed a primitive type of lung. It is not surprising, therefore, that along another line of

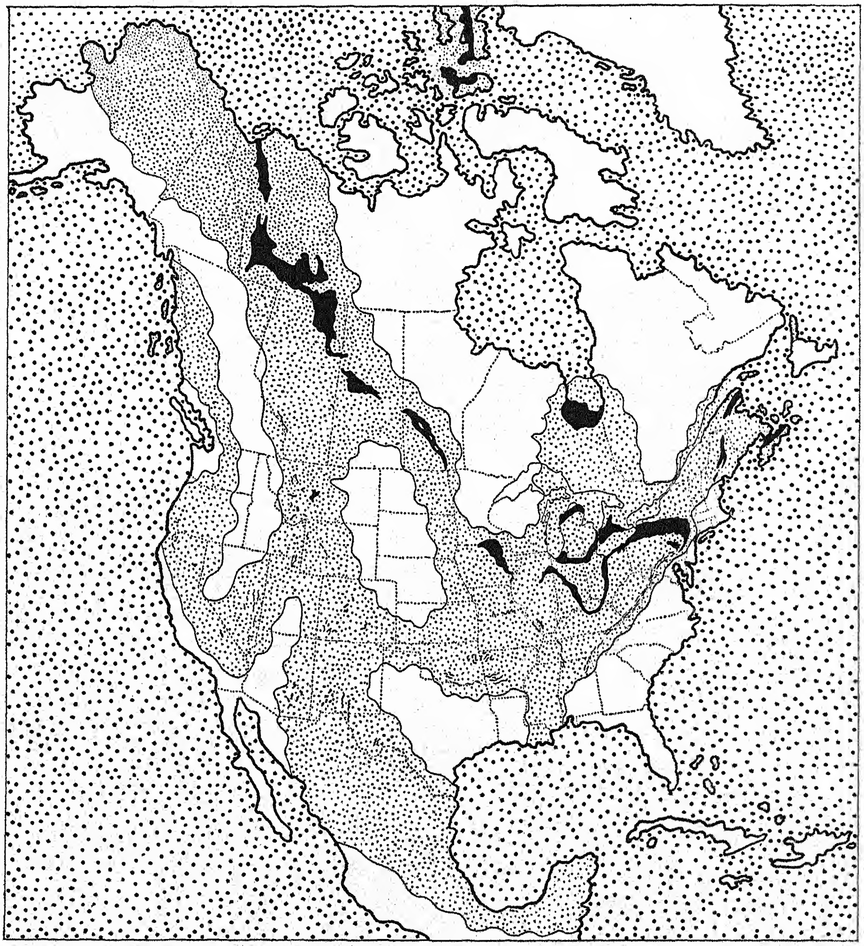

FIG. 363.—Devonian seas. (*Modified from Schuchert.*) Fine stipple represents areas of epicontinental seas. Black represents outcrops.

evolution an efficient lung should develop and paired legs with walking feet should appear. This next higher step in the evolution of the vertebrates was the amphibians that left evidences of their presence in the late Devonian. The evidences are not extensive, just a track in the upper Devonian of Pennsylvania and a few bones in Latvia. There is a possibility that lung development lagged behind the development of the feet. Amphibians are cold-blooded animals that breathe by

means of gills in the early stage and by means of lungs in the later stage. They differ from fishes not only in having legs and feet and in having lungs but in having developed a three-chambered heart rather than the two-chambered heart of the fishes.

Scorpions, the First Lung Breathers.—While the seas were drying up in New York, Ohio, and Ontario, they forced various life adjustments to

FIG. 364.—On the left an amphibian footprint from the Devonian. (*From Pirsson and Schuchert, after Lull, courtesy of John Wiley and Sons.*) On the right a hypothetical Devonian amphibian. (*After M. G. Mehl.*)

changing environment. The sea animals that lived in these inland bodies of water would surely have died off had the seas dried up very rapidly or dried up within a few thousand years, but with the slowness of the drying there was opportunity for adjustment to the new conditions. The animals might start living part of the time in water and part of the time on land and finally develop the ability to live on land all of the time and breathe air. Whether this was the cause or whether something else forced it, the first of the air-breathing animals appeared on the shores of these old seas in the third period of the Paleozoic. These first air breathers were scorpions. The air-breathing vertebrates, as the lung fishes and the amphibians, did not develop from the scorpions. The ability to breathe air was an independent development in all three types.

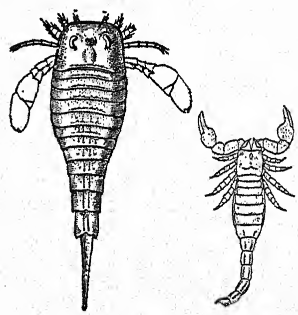

FIG. 365.—Scorpion on the right (*after Pocock*). Eurypterid on the left (*after Clarke and Ruedemann*). (*From Pirsson and Schuchert, courtesy of John Wiley and Sons.*)

The Oldest Forests.—At some time during the Middle Paleozoic plants of large size grew on land and a record of the first forests occurs in the Devonian of New York state. The fossil trees were uncovered at the time the excavations were being made for the new water system of New York City. Stumps of trees and trunks 2 or 3 feet in diameter were found there in abundance. They belonged to the fern group of plants and not to the higher group to which most trees of the present belong. Up to this time all of the main groups of plants had appeared with the exception of the highest. Botanists divide plants in four great groups, which they call thallophytes, bryophytes, pteridophytes, and spermatophytes. The first includes one-celled forms and others of very low organization. The bryophytes are the moss group, the pteridophytes the fern group, and the spermatophytes include all of the forms higher

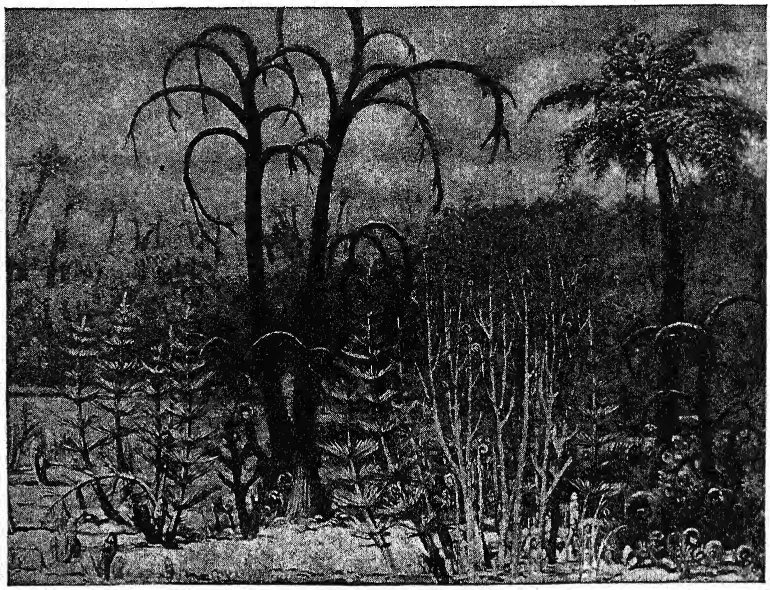

FIG. 366.—A Devonian forest. (*R. C. Moore, Historical Geology. From a painting by C. R. Knight in Field Museum of Natural History, Chicago.*)

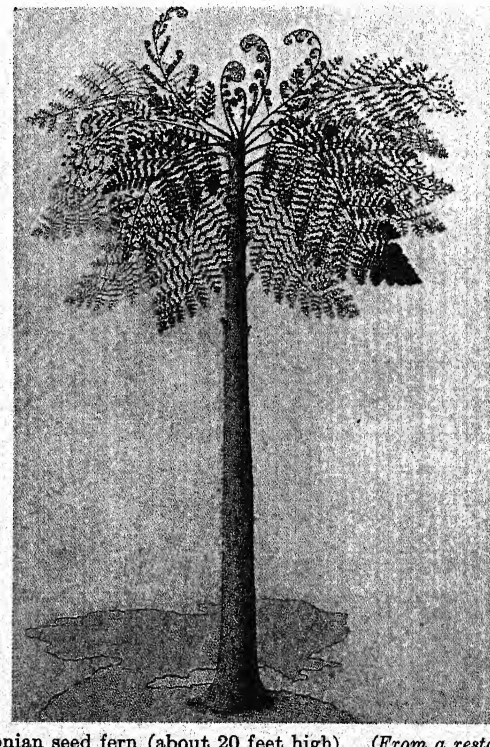

FIG. 367.—A Devonian seed fern (about 20 feet high). (*From a restoration in New York State Museum by Winifred Goldring. Courtesy of New York State Museum.*)

than ferns. There are fronds, however, that looked so much like fern fronds that anyone at all familiar with ferns could recognize them.

Thin coal seams occur in various parts of the world and many of the Devonian shales are highly carbonaceous. Some of those in northern Ohio have so much plant material in them that they will burn. However, much of the carbonaceous material in the rocks came from plants that grew in the seas rather than from land plants.

ECONOMIC PRODUCTS

Salt.—As we have already considered the salt and gypsum as peculiar rocks of the Middle Paleozoic, we may consider these two first among the economic products. The salt supply for the entire United States used to come largely from the Silurian of New York and Ohio, but the development of salt mines in other parts of the United States has restricted the use of this salt to eastern and east central United States. The salt is not actually mined; most of it is dissolved and brought to the surface as a brine and then reevaporated to separate the sodium chloride from other salts. When the seas in which the salt was formed dried up, salts more soluble than sodium chloride were deposited; and in dissolving out the material from underground the more soluble salts dissolve first. In separating the salts after they come out the sodium chloride is taken out first and the other salts are drawn off in the mother liquor. Potash salts are among the more valuable of those of the more soluble type.

Gypsum and Other Quarry Products.—Gypsum is quarried and its main use is as plaster of paris for interior plaster of houses and other buildings. It is also used for modeling purposes, for making building blocks, crayons, etc. Most of the gypsum from the Middle Paleozoic is quarried in Ohio and New York. Making natural cement was once an industry of importance and derived much of its raw materials from the Middle Paleozoic rocks. Portland cement, now very extensively used, has largely taken the place of natural cement and is better material on account of being more uniform. The natural cement was made by burning to clinker stage a limestone that contained about 20 per cent clay. As limestones vary greatly in composition, even within short distances and between different layers in the same bed, much of the quarried product had to be rejected because it contained either too much clay or too little clay. For Portland cement the materials are analyzed chemically, just the right proportion of the right shale or clay is mixed with the limestone, and the resulting product from any particular plant is quite uniform. Flagstones from the Devonian were formerly used in making sidewalks and roads but their use has been largely discontinued with the development of cement; the use of Devonian limestones and shales in the manufacture of Portland cement is extensive. Limestones and shales of almost any period may be used in this manufacture; the ones selected

for use depend largely on the accident of location of their outcrops in the vicinity where it is desired to locate the cement plant.

Oil and Gas.—Oil and gas occur in rocks of both these periods in West Virginia, Pennsylvania, Ohio, and Kentucky, but the production is not large and no big field has been developed any place in Middle Paleozoic rocks.

Iron.—Much of the iron produced in the United States previous to about 1854 came from the Silurian of the Appalachian Mountains from Pennsylvania southward to Alabama. An arm of the Silurian seas extended through the Appalachian Trough and the waters coming to it were highly charged with iron in solution. This iron precipitated on the sea bottom, in some places with calcium car bonate and clay, and in still others with sand. In places the ore is made up of little grains resembling flaxseed and it was named flaxseed ore on that account. In places the iron content was high enough to make it an iron ore but in most places the content was too low. When iron smelting was done by charcoal burned in the region and the amount of iron produced in any furnace was small and for local consumption, hundreds of furnaces were located near the places where the iron was mined. When the Lake Superior iron began to be produced the small mines along the Appalachians were gradually abandoned and nearly all mining of this ore centered about Birmingham, Alabama, which now has the most important iron production outside the Lake Superior region. The Birmingham district has some advantages over that region in that it has an abundance of coal and limestone, used in smelting. Although the ore is of lower grade than in the Lake Superior region, pig iron can be produced as cheaply there as from the better ores.

CLIMATE OF MIDDLE PALEOZOIC

The evidences concerning climate of the Middle Paleozoic are based largely on the distribution of sea animals. As we have considered in the physical part of this book, corals live almost altogether in tropical waters, particularly the reef-building corals, and these are widely distributed in latitude in both of the Middle Paleozoic periods. During the lower of these periods, the Silurian, there seems to have been a path of migration for animals from North America to Europe directly through the polar regions, as the same species are found in central North America in the vicinity of Chicago, in the northernmost part of North America, in Spitzbergen, and in Sweden, and these species are not found generally distributed in the Silurian rocks. The presence of the same marine invertebrates in what is today the polar regions and warm temperate regions indicates a rather uniform temperature of water at that time. There are no positive evidences of seasonal variation in the fossil plants but those might not be present in the type of plants which grew at that time.

CHAPTER XXI

UPPER PALEOZOIC

In the Upper Paleozoic many geologists recognize only one period, which they call the Carboniferous and which they divide into Mississippian, Pennsylvanian, and Permian. Other geologists consider that each one of these is deserving of period rank. The names of all of the Paleozoic periods preceding the upper were derived from the British Isles. The term Carboniferous was applied on account of the extensive coal deposits which occur in the Pennsylvanian. Mississippian was adopted because of the great development of rocks of this age in the Mississippi Valley, Pennsylvanian on account of the state of Pennsylvania being so largely made up of middle Upper Paleozoic rocks, and Permian from the province of Perm, Russia. Permian is the only departure from western European or American names among the names of the periods.

Geography of the Upper Paleozoic.—During the Mississippian period the extent of seas on the North American continent was not greatly different from other Paleozoic periods. The Appalachian Trough formed an early seaway as usual, and seas were widespread in the interior and in the Rocky Mountain regions. Pennsylvanian geography departed widely from other periods. Seas advanced and retreated many times over the same region, as many as 60 advances and retreats being known. The retreats were rapid and the lands were at all times so low that swamps covered most of them. From the Appalachian region to eastern Kansas and Nebraska half of the area above sea was in swamps during several of the land stages.

The marine deposits are recognized by the fossils they contain and the swamp deposits were mainly plants that later became coal and at present constitute the great coal reserve of the states from Kansas to Pennsylvania. The rocks associated with the coal are mainly shales, but sandstones are important and thin limestones make up part of the marine formations. Erosion was vigorous during some of the sea withdrawals. In the older formations river channels filled with sands deposited from younger seas are common. In Kansas and Oklahoma some of these channel deposits bear oil.

In the province of Perm, Russia, much of the Permian consists of red sandstone, and in the Rocky Mountain region and Oklahoma red sandstones are important. These are usually called red beds, although all of them have been given formation names.

Shallow-water Deposits.—A striking peculiarity of the Appalachian Trough sediments is that most of them show evidences of having been deposited in shallow water. Ripple marking is common in the rocks of every period. Rapid alternation of coarse to fine sediments is present in every period. Shallow-water fossils occur in nearly every formation. Mud cracks are present in hundreds of members.

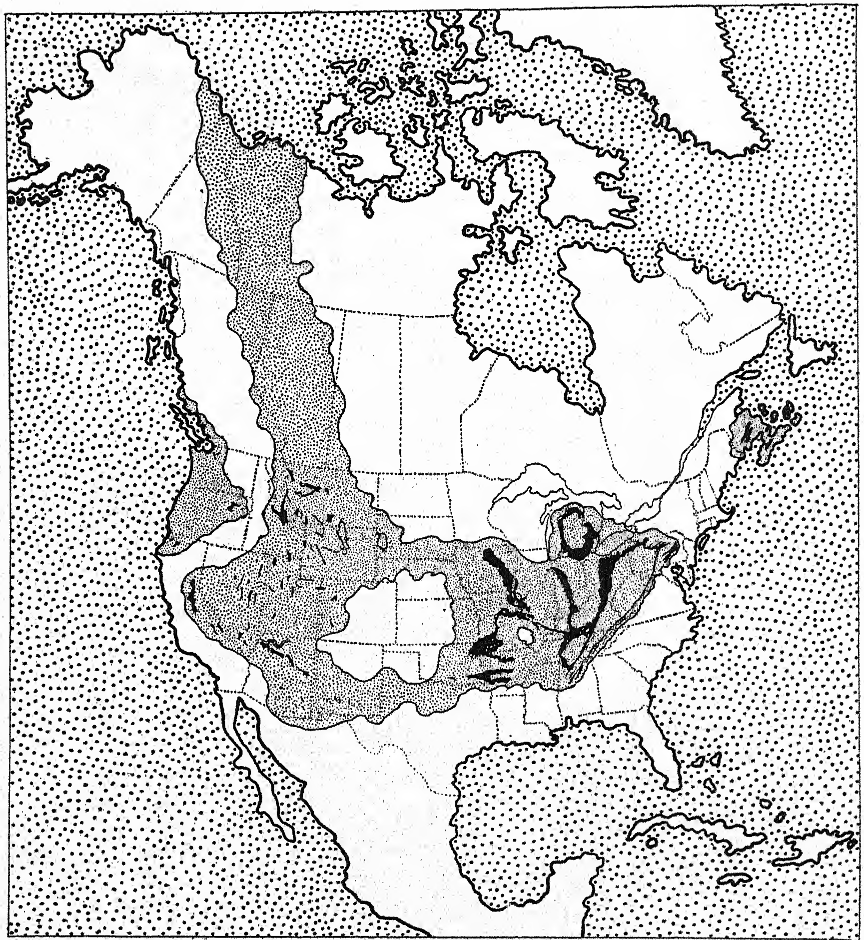

FIG. 368.—Mississippian seas. (*Modified from Schuchert.*) Fine stipple represents epicontinental seas. Black represents outcrops.

In order to have 40,000 feet of sediments deposited in shallow water the bottom of the trough must have been sinking at about the same rate that the sediments were being deposited. At some times sedimentation was the more rapid, and widespread topset beds of deltas and alluvial fans formed.

End of the Appalachian Trough and Close of the Paleozoic Era.—With the close of the Mississippian the Appalachian Trough ceased to be

a permanent seaway and from an area of deposition became one of erosion. During the Pennsylvanian it was above water most of the time and in the Permian it was folded and faulted into the Appalachian Mountains. The sides of the trough were pushed 40 to 50 miles closer together than they had been before, and many sharp folds of large size developed which involved strata several miles in thickness. During the Paleozoic some

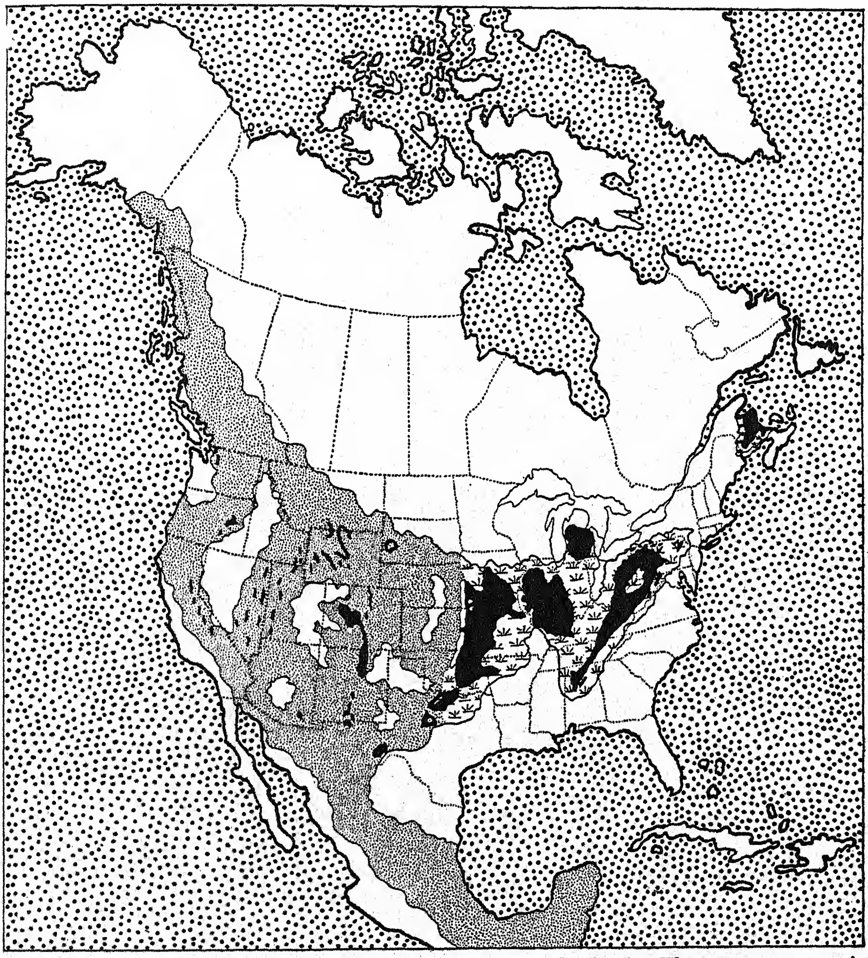

Fig. 369.—Pennsylvanian seas. (*Modified from Schuchert.*) The swamp areas in eastern and central United States represented by dashes and lines. The epicontinental seas in western United States represented by fine stipple. Black represents outcrops. Seas covered the swamp areas during part of the period.

40,000 feet of sediments were deposited in the trough. As few unconformities of importance appear in the section, it appears that the trough area was above sea only a few times during the Paleozoic.

Before the close of the Pennsylvanian the seas withdrew to a Gulf of Mexico extension which reached as far north as Nebraska and as far west

as Arizona. This sea continued on into the Permian and the boundary between the two periods is uncertain, as no unconformity exists. During the Permian the seas became more and more restricted and finally completely withdrew to the ocean basins.

Emergence of the Lands.—The folding of the Appalachian Mountains changed geographic conditions so much that the later history of the region and of the adjacent territory was radically different from that of earlier times. Seas never again occupied the Appalachian Trough, although they overlapped parts of it.

At the end of the Permian all of North America emerged; no place is known where Paleozoic sediments grade into Mesozoic without unconformity, although in some places no unconformity can be identified positively. Not only did a period of erosion of the entire continent set in but it lasted well into the Triassic, the first period of the next era, over most of the continent.

LIFE OF THE UPPER PALEOZOIC

Trilobites.—Inasmuch as Middle Paleozoic changed to Upper with no conspicuous geographic changes, striking life changes were not to be expected. There was a rather gradual evolution of the forms already present. Old-age characteristics of the Devonian trilobites faithfully foretold the coming results; few trilobites were left in the Mississippian and they were small and most of them without ornamentation. From some 200 species in the Devonian they dropped to about 20 in the Mississippian, and even where other fossils are abundant one rarely finds a trilobite. In the Pennsylvanian they are still rarer and only a few species are known from the Permian.

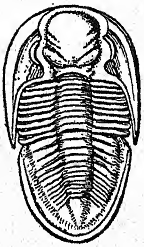

FIG. 370.—A Pennsylvanian trilobite, one of the last of the race. (*After Keyes, Mo. Geol. Survey.*)

Brachiopods.—The brachiopods retained their leadership in numbers of species and individuals and displayed no conspicuous signs of old age. Two types known as spirifers and productids dominated and made up nearly half of the 800 species known from the Upper Paleozoic. Productids were degenerate forms in some respects. They had lost their pedicle, a fleshy stalk by means of which most brachiopods were attached. Productids have one very convex shell and one that is concave (Fig. 378).

Crinoids.—Another group of invertebrates, the crinoids, became conspicuous. As one member of the Echinodermata, they are related to modern starfishes and sea urchins. They consist of a cup or head, with radiating arms, that contains the vital organs. Most crinoids have a long stem by which they attach themselves to the sea bottom. The joints of the stems have a hole in the middle and some Indians used them as beads. Some Mississippian rocks are composed almost entirely of

these stems, which do not show conspicuously on freshly broken surfaces but weather out in relief. Over wide areas of the Mississippian sea bottom the crinoids must have lived close enough together to appear like fields of grain. Crinoids occur for the most part in limestone because

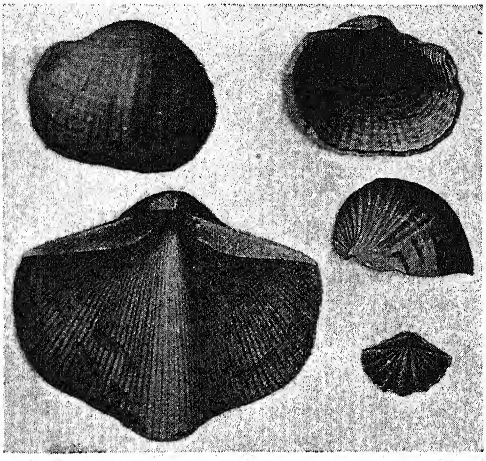

FIG. 371.—Mississippian brachiopods of the dominant genera, *Productus* and *Spirifer*. (*After E. B. Branson, Kinderhookian of Missouri.*)

they were chiefly clear-water dwellers. They became rare in Pennsylvanian and Permian time.

Insects.—Insects of considerable variety were present. They first appeared in the Pennsylvanian and some kinds became abundant.

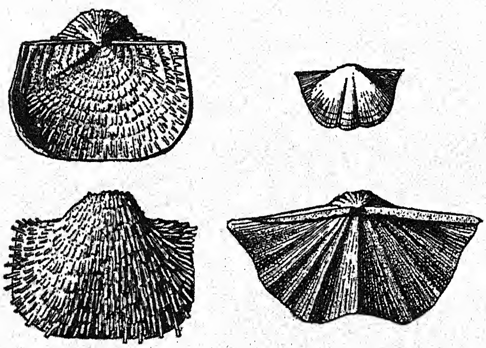

FIG. 372.—Pennsylvanian brachiopods of the dominant genera, *Productus* at the left, *Spirifer* at the lower right, *Chonetes* at the upper right. (*After Beede, Univ. Kansas Geol Survey.*)

Permian rocks contain remains of cockroaches several inches long. Dragon flies with wing spreads of nearly two feet were the most conspicuous kind (Fig. 376). Many other less startling developments filled out the list.

Sharks.—In the Devonian sharks appeared as inconspicuous members of the class of fishes. In the Mississippian they developed rapidly, and in one of the formations more than 400 species are known. They developed along two lines that were strikingly different. In one the teeth were sharp, tearing teeth, like those of most modern sharks; while in the other they were flat, crushing teeth, some of them 2 or 3 inches in diameter. Sharks' bones are made of cartilage and do not have lime laid down in them so as to make them hard like ordinary bone. On that account they are only rarely preserved as fossils, and the remains of sharks found in the rocks are mainly teeth and spines.

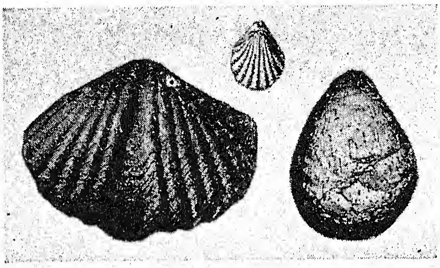

FIG. 373.—Permian brachiopods of the genera *Spirifernia* at the left, *Hustedia* above, *Aulosteges* at the right. (*After C. C. Branson, Paleontology and Stratigraphy of the Phosphoria formation.*)

In the Pennsylvanian sharks decreased rapidly, few lived to the upper part of the period, and very few lived over into the Permian.

Amphibians.—Amphibians appeared first in the Devonian and their remains are very rare in the Mississippian. The conditions of land and water in the Pennsylvanian were exceedingly favorable for the amphibians and they expanded rapidly. All were small and inconspicuous, but some of the swamps must have fairly swarmed with them. In the Permian their development continued and some of the largest ever found lived then. They were short-legged, broad, and short. In spite of their

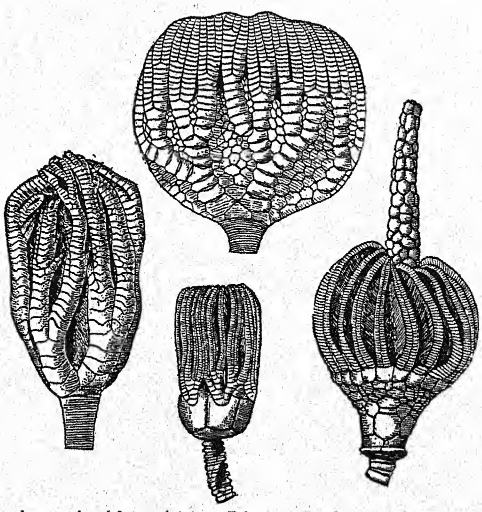

FIG. 374.—Mississippian crinoids. (*After Pirsson and Schuchert, courtesy of John Wiley and Sons.*)

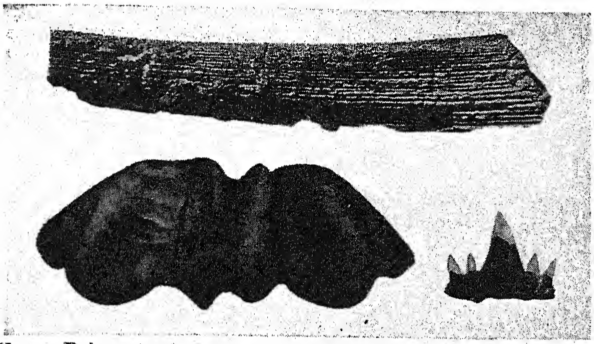

FIG. 375.—Upper Paleozoic sharks' teeth and a shark spine. (*After E. B. Branson.*)

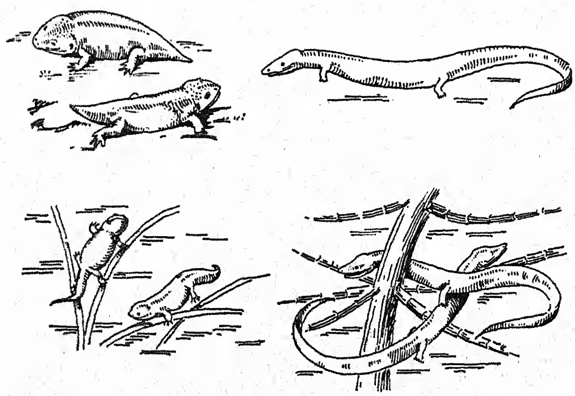

FIG. 376.—Amphibians from the Pennsylvanian (those on the left about four inches long; on the right, about eighteen inches long). (*After Osborn, "The Origin and Evolution of Life."*)

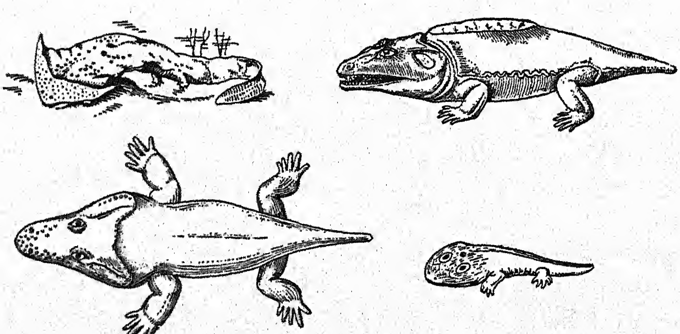

FIG. 377.—Amphibians from the Permian (those on the left, about five feet long; the upper right, about two feet long. The lower right is a hypothetical form about eight inches long). (*Upper left after Osborn, the others after Williston.*)

comparatively recent development some of the amphibians had degenerated to such an extent as to have lost their legs.

Reptiles.—While the numerous changes were taking place in the amphibians the reptiles branched off from them. The oldest remains of reptiles known are from the Pennsylvanian, about the time when amphibians were evolving so rapidly, but only a few specimens are known from the Pennsylvanian. In the Permian the development of reptiles came with a rush and many strange forms have been collected. None of them, excepting one lizard-like form, belonged to any of the modern types. Most of the Permian reptiles of North America have been collected from Texas, where continental deposits were formed favorable for the preservation of their skeletons. The most remarkable of these reptiles had long, slender spines extending upward from the arches of the vertebrae, giving to the top of the body a peculiar sail-like appearance with the sail extending lengthwise of the body. A specialized form had crosspieces on the bony spines, making each appear like the mast of a ship with cross arms.

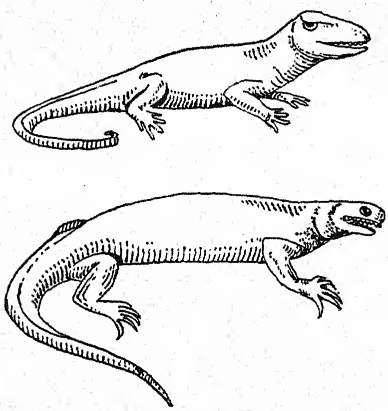

Fig. 378.—Reptiles from the Permian, upper about seven feet long, lower about four feet long. (*After Williston.*)

Changes from Amphibians to Reptiles.—The differences between reptiles and amphibians are not great as they are shown in the skeleton, the only part preserved as fossils. The real distinguishing characteristic is that in the early life of the amphibians they breathe by means of gills, and reptiles never breathe with gills. The difference is not so large as it seems because the gills are also present in the reptile but only in the embryonic stage. In the process of evolution of reptiles the lung-breathing stage developed earlier and earlier in the life of the individual until the change to lungs came in the embryo. In some ways this proved an advantage and was perpetuated, giving rise to the reptiles. When changes start in a particular direction, they may go past the most advantageous stage if the changes are rapid and vigorous and may give rise to animals unfitted for any environment except the one into which they were born. This did not happen with the reptiles in the early stages in the Pennsylvanian, but in the Permian almost any sort of monstrosity might be expected on account of the rapidity of the changes that were taking place.

The vertebrate land life of the latest Paleozoic was entirely reptiles and amphibians, with possibly a minor development of lung fish. No birds or mammals were present. The Permian reptiles were probably

no more abundant than reptiles at the present time and the land was poorly supplied with life. There were no forms as big as the modern crocodile and none of the modern forms was present.

Extinction of Many Reptile Groups.—A striking thing about the Permian reptile groups was their complete disappearance. To say complete disappearance probably conveys the wrong impression, although the several groups seem to have left no descendants. Most forms disappear by changing gradually so that the old kind by which they were known is no longer present. The changes in 100,000-year periods would not be great enough to obscure the relationships, but the lost time between Permian and the next period, when preservation of reptiles was such as to enable investigators to study their anatomy, was in tens of millions of years. For most forms it is impossible to determine the ancestral form. Of the modern groups it is not known from what Permian group turtles, lizards, snakes, or crocodiles came.

Plants.—The Mississippian contained no plants that need special mention. In places plants were very abundant and in some places coal formed. The reason for only a small amount of coal forming was probably absence of swampy conditions rather than scarcity of plants.

In the Pennsylvanian came the great time of plant growth of the Paleozoic. The swamp conditions of the period have been described in another paragraph and the swamp growth may now be described. Apparently in the lowlands water plants grew in such profusion as actually to fill the swamps with dead plant remains. In places the spores of the fern group of plants accumulated in such quantities as to form beds of coal. In parts of the Mississippi Valley sink holes had formed in the older rocks during early Pennsylvanian time and these were a favorable place for the lodging of spores. Cannel coal, made up of spores, developed in the sink holes, and in some of these holes beds were formed more than 50 feet in thickness.

Scouring rushes and club mosses reached the greatest size of any of the trees, some more than 100 feet tall and 6 feet in diameter (Fig. 379). The modern representatives of these groups are small herbs. Tree ferns were abundant and smaller-sized ferns grew in great profusion. The most significant of all of the plants was one that seemed half way between the ferns and the seed-bearing plants. It had leaves like a fern but bore seeds. This was the beginning of the highest type of plants, the spermatophytes or seed-bearers, which now dominate the plant life of the world.

Reduction of Plants.—The most remarkable thing about the plant life of the late Paleozoic was its decline toward the close. From thousands of species in the Pennsylvanian it was reduced to a few hundred in the late Permian and not one of these passed over into the Mesozoic. The failure to pass over is not of high significance as the time between the latest fossiliferous Paleozoic and oldest Mesozoic may have been more

than 10,000,000 years. (For the sparse vegetation of the Permian see Figs. 381 and 382.)

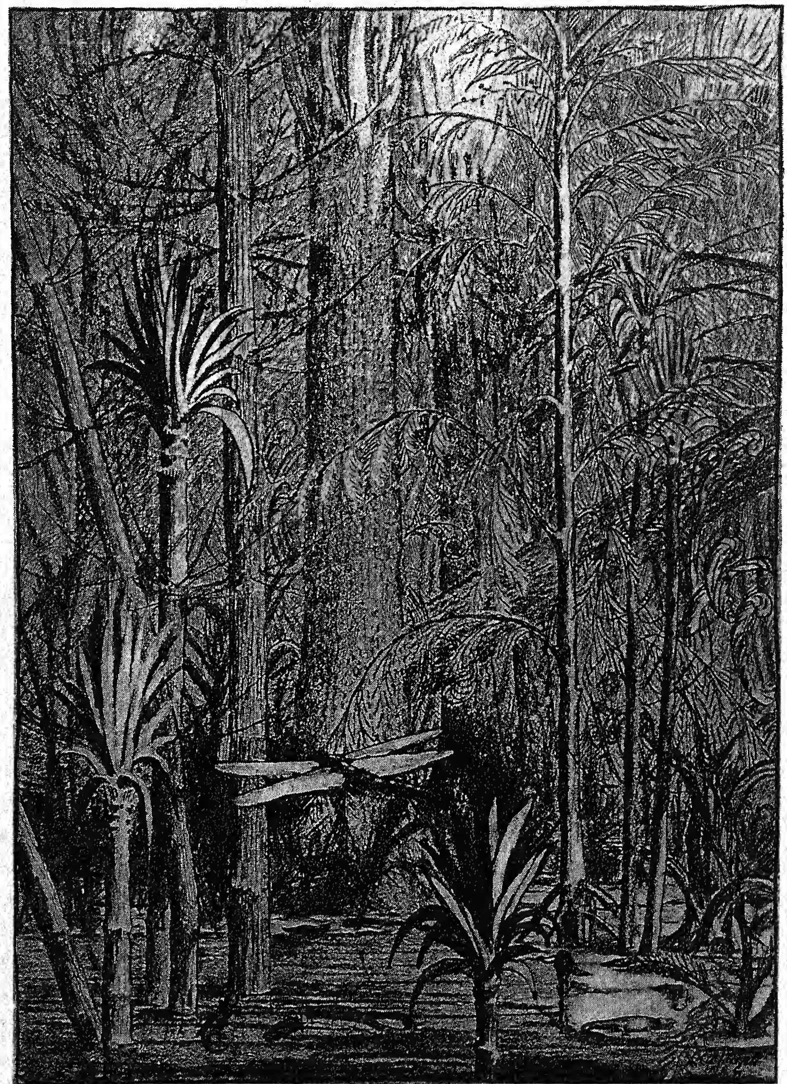

Fig. 379.—Life of a Pennsylvanian swamp. A large dragon fly in the foreground, several small amphibians in the water. (*From M. G. Mehl.*)

Permian Climate Unfavorable to Plants.—The Permian conditions were much more trying for plants than for animals, but the lack of plant fossils may be somewhat misleading. At the present time about one-third of the land surface is desert, and although deserts may grow plants of many kinds, few of them could be preserved as fossils because they

contain too little woody tissue. Another reason is that they are unlikely to fall into water and get covered with mud so as to have the materials in solution in the water penetrate the tissues and change them to solid rock.[1] Probably more of the earth's surface was arid in the Permian than at present and smaller areas were favorable for plant preservation. But still another factor entered into the plant problem of the Permian. The increasing cold brought on glaciation over large areas and subjected plants to rigorous conditions. With continental glaciers extending into the tropics in Africa, Asia, and Australia, conditions for abundant plant growth were present during part of the time in only limited areas in those parts of the world. The question may be raised as to why, with such glaciation in other parts of the world in the tropics, reptiles could live in such abundance in Texas and marine life flourish in the seas nearly as far north as the Arctic Circle.

Climatic Changes during a Period.—Glaciers develop only in regions of abundant snowfall and could not form in Texas where the climate was arid. But that does not fully answer the question, for reptiles do not live in cold climates and Texas could be just as cold without glaciers as with. Glacial deposits are conspicuous in the Permian but that does not mean that the Permian was cold in those places during the entire period. The period must have lasted at least 30,000,000 years and 1,000,000 was long enough for the glaciation. Pleistocene glaciation may not have lasted more than 1,000,000 years and that gave time enough for five advances and five retreats of the ice and for tropical plants to grow 500 miles north of the extreme southern boundary of the ice during an interglacial period. It is possible then to have boreal and tropical plants growing within the same area within a small part of one period, to have a continental glacier cover an area and tropical plants grow in the same area within 500,000 years. Texas may have been cold enough for glaciers to form there during the same time that they were present in India, but the Texas Permian history that we have been considering may have long been over. The same consideration may have been true for aridity as for glaciation. A region arid during part of a period may have been well watered during another part. The area arid during the last part of the Silurian was under the sea during much of the period.

In India, Australia, and Africa a flora developed under the influence of glaciation during late Paleozoic and finally spread over most of the world. It is called the Gondwana flora from its supposed spreading

[1] Plants fossilize in other ways than being petrified. A plant may fall into mud and become completely covered with mud. After the mud becomes solid the plant tissue may decay and be removed and the cavity be filled with sand or clay. This creates a cast of the original trunk just as a cast is made of iron in an iron foundry. Fossils formed in this way contain none of the cell structure such as is preserved in petrified plants, but the exterior is reproduced in great perfection.

across Gondwana land. The flora was made up largely of ferns and related forms and contained no tropical elements.

Permian and Its Life.—The landscape in Texas during the period was perhaps typical. The area was low, something like the delta of the

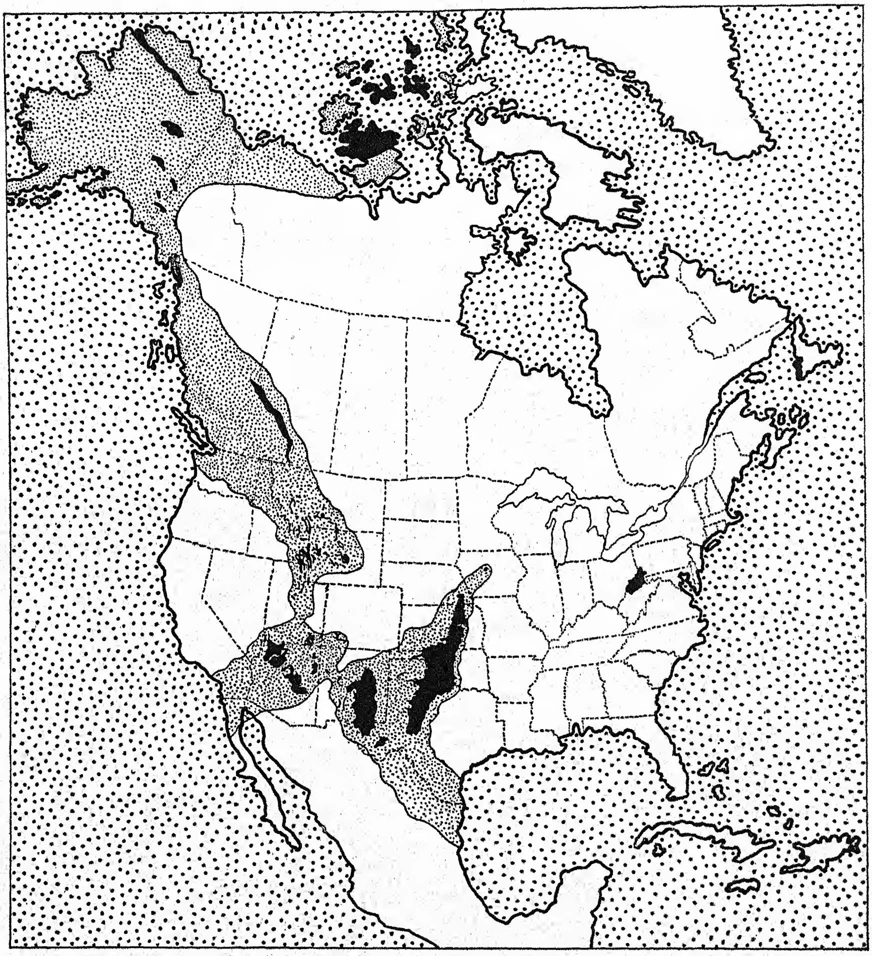

FIG. 380.—Permian epicontinental seas in fine stipple, outcrops in black. (*Seas modified from Schuchert.*)

Mississippi at the present time. Vegetation may have been fairly abundant but not so plentiful as it is in the moist tropics today or as it had been in the Pennsylvanian. It was more like that at the mouth of a great river in a semiarid region. There were no flowering plants among the trees; the plants were mainly of the fern group, bearing no seeds and reproducing by spores only. There were no grasses among the small plants, but ferns and scouring rushes were abundant.

The streams in this region were bringing in mainly red sands and clays to deposit as red beds. Northward and westward lay the enclosed seas in which gypsum and salt were depositing, and the lowlands on which the red sands were being deposited were part of the old basin of one of these seas that had been laid bare by the drying up or withdrawal of the seas. Part of the deposits were alluvial fans and parts were the topset beds of deltas. Here and there the wind piled up loess, adobe, and sand.

Most of the animals lived near the stream courses, but in the lowlands water was abundant enough for favorable habitat. On these lowlands

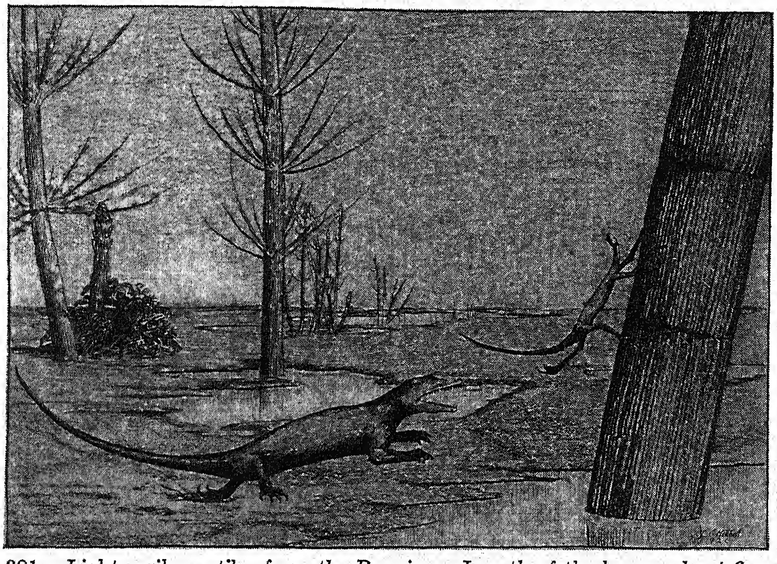

Fig. 381.—Light, agile reptiles from the Permian. Length of the larger, about five feet. (*From M. G. Mehl.*)

the reptiles and amphibians lived, but their remains were preserved as fossils only under exceptional conditions. The oxbow lakes formed by cut-off meanders were favorite drinking places for animals, and the muds in such places were finer and buried animals more efficiently than the ordinary floodplain deposits. The chance for the bones to be covered with water and mud was better there than elsewhere and therefore the chance for fossilization was better.

Animals as large as most vertebrates stand little chance of dying without other animals eating the flesh and scattering the bones. If the carcass can be covered with mud soon after the animal dies so that other animals find it difficult to disturb it, the chance for fossilization is greatly increased. If the animals were preserved mainly in oxbows their remains would be found only in an extremely small part of the total area. Such is the case with the Texas reptiles; one may search for days over the deposits without finding a bone and then he may find remains of several individuals near together.

Highlands should be included in the picture as well as lowlands. The uplift of the Arbuckle and Wichita Mountains and the extension of that line of folding through Arkansas to the main Appalachian Mountains was taking place during the Permian. Streams were rejuvenated and

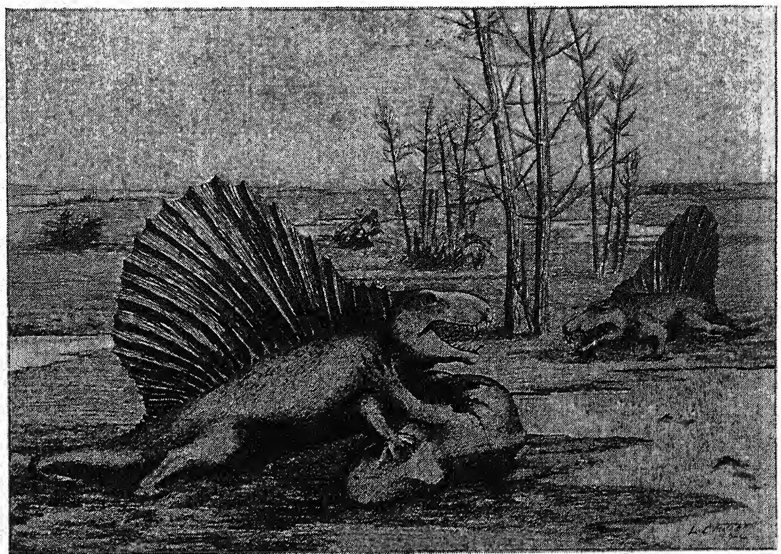

FIG. 382.—A Permian fin-backed reptile eating a large amphibian (reptile about eight feet long). (*From M. G. Mehl.*)

became vigorous near their headwaters, and were sluggish only where they came to the old sea flats.

The rivers contained lung fishes and primitive bony fishes as well as small clams. The highly saline seas had no life in them, but the open seas were separated from the inclosed parts only by sand bars in many places. On one side of the bar there were no animals while on the other life was abundant. The fisherman drawing his nets through the inhabited sea would have brought out mainly brachiopods, among which the concavo-convex shelled productids would have been dominant. He would have worked for a long time before securing a trilobite or a crinoid. In some places cephalopods would have been the main catch. If he had used a very fine-meshed net he might have secured great numbers of shells of one-celled animals of the type which made up a great deal of rock in the Pennsylvanian and were very abundant in some parts of the Permian.

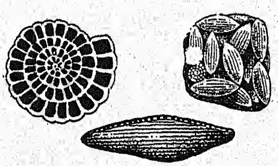

FIG. 383.—Foraminifera, one-celled animals, that made up large amounts of Pennsylvanian rock (about six times natural length). (*After Keyes, Mo. Geol. Survey.*)

The Wyoming Sea Life.—If he had crossed the divide from the sea that was drying up in Kansas to a sea that occupied part of Wyoming and tried his net there he would have found some of the shallow parts inhabited mainly by forms very rare in the southern seas. One brachiopod that had an almost circular shell (its name is Orbiculoidea), composed of lime phosphate, rather than of lime carbonate, was abundant. These shells accumulated in such numbers that they made a rock largely composed of phosphate, which is used as fertilizer where it can be put on the market without too great cost. The net would still have brought in mainly brachiopods, with the productid type the dominant one.

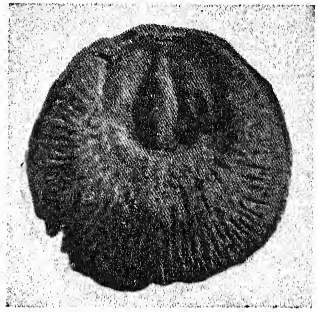

FIG. 384.—A brachiopod with phosphatic shell, abundant in northwestern Permian sea of the United States.

Recapitulation of Paleozoic Life.—In the Cambrian period the seas brought in the first abundant life, which consisted mainly of brachiopods and trilobites. In the Ordovician many new groups of animals originated, most significant of which were the cephalopods and fishes. The trilobites and brachiopods increased in numbers over those of the first period but they no longer dominated. In the Silurian scorpions—the first air breathers—are known from the shores of the lakes which dried up late in the period. In this period coral reefs appear for the first time. The Devonian or fourth period is known as the Age of Fishes owing to the great expansion and development of the group during this time. During the same period the amphibians, next higher group of vertebrates, appeared. During the Devonian the trilobites began to take on old-age characteristics which preceded their disappearance. In the Devonian also the first forests appeared.

The remarkable things about the life of the Mississippian were the development of the crinoids and the great expansion of the sharks. In the Pennsylvanian the amphibians gave rise to great numbers of highly varied forms and the reptiles evolved from them. Insects appeared for the first time. The expansion of plant life was one of the significant things and particularly the formation of coal from the plants.

The final period saw the remarkable evolution of strange reptiles, the development of large amphibians, the final dominance of the brachiopods, and finally the beginning of great reduction in all types of life and the complete disappearance of some great groups, the trilobites being the most remarkable.

ECONOMIC PRODUCTS

The Upper Paleozoic is the most important time for economic products in geologic history. The Mississippian contains much oil and gas in

Pennsylvania, Ohio, West Virginia, and Illinois. The oldest workable coal in North America is in the Mississippian of Virginia but it is of little importance. A delta was built into the Appalachian Trough and in the swamps on the top the Mississippian coal formed. Important building stones are quarried in several places and limestone for the manufacture of cement. The Bedford (Mississippian) limestone of Indiana is the most important building stone. It is fine-grained and is the oldest rock in North America made up mainly of the shells of one-celled animals or protozoa. Nearly every large city east of the Mississippi River has many buildings constructed of this stone. The Berea sandstone (Mississippian) of northern Ohio is another well-known stone which is widely used. It is quarried and sawed into blocks or left rough according to the use wanted. The bedding is even and in many parts of the quarries split into the right thickness for building. The stone was formerly used extensively for sidewalks and was sawed into slabs 2 or 3 inches thick for that purpose. The formation is extensively ripple marked and on wear the ripples would appear on the sidewalk surfaces, making them too rough for best usage. Some layers in the quarries are used extensively for abrasives, particularly for grindstones. Most of the grindstones used in the United States are made in northern Ohio from these rocks.

The Burlington limestone (Mississippian) of Iowa and Missouri has a number of quarries, one of the best known being at Carthage, Missouri. Here the rock is so compact and even-grained that it takes a good polish and is used as marble. The formation is peculiar in being made up very largely of crinoid stems and other parts of crinoids. More crinoids have come from it than from any other formation in America, and fine collections of them are in many museums.

Zinc and Lead.—In southwestern Missouri and adjacent parts of Oklahoma and Kansas great numbers of sink holes formed in Mississippian limestone before Pennsylvanian time and when the Pennsylvanian seas came over the region they washed the residual cherts from the hills into the sink holes and other valleys and later covered the entire region with clay that now forms extensive shale deposits.

Circulating ground waters carrying lead and zinc in solution deposited materials from solution between the pieces of chert that filled the sinks. They carried a great deal of calcium, silica, iron, and sulfur in addition to lead and zinc, and the resulting deposits were a heterogeneous mixture of all of these. The minerals were calcite, quartz, galena, sphalerite, and pyrite cementing together the pieces of chert. Crystals of calcite 6 inches in diameter are not rare and masses of galena and sphalerite weighing several hundred pounds have been found. This is the most important zinc-producing region of the world, and lead to an amount about one-fourth as great as the zinc comes from the same region. It is usually known as the Joplin district, as Joplin was the main city of the

region until recently. The main mining is now in Oklahoma and Kansas, as the ore is richer there than that left in the ground in Missouri.

Coal.—The Pennsylvanian is the great mineral producer, as the two mineral products most important in amount and value come from it. About 90 per cent of the coal mined in North America comes from rocks of Pennsylvanian age. All of the coal east of eastern Kansas is of this age, except small deposits in Virginia and North Carolina. Pennsylvania is the most important coal-producing state and contains both anthracite and bituminous deposits of importance. The only important anthracite deposits in the United States are in the northeastern part of the state and cover only a small area. The rocks in which they occur were intensely folded and the change from bituminous to anthracite probably took place during the folding (page 359). Since the folding erosion has removed most of the coal-bearing strata and many times as much anthracite has been carried away by streams as has been left to be mined. The finest deposit of bituminous coal is the Pittsburgh bed known as the black diamond coal; it was largely responsible for the growth of various manufactories in Pittsburgh. It cokes readily and is important for smelting iron. Many of the early iron mines were near enough to Pittsburgh to cause the smelting industry to grow up there, and when the richer iron deposits of the Lake Superior region were discovered it was cheaper to bring the ore to Pittsburgh than to ship the coal to the ore.

The Pittsburgh vein underlay an area of 2,100 square miles, averaged about 7 feet thick, and was of very high-quality bituminous. In spite of its thickness and extent it is nearly exhausted and coal will be shipped from distant fields to Pittsburgh within a few years. For the accumulation of the Pittsburgh bed of coal a swamp with an area of possibly 3,000 square miles must have existed for many thousands of years.

In some places in Pennsylvania and West Virginia more than 20 beds of coal are present in the same section and beds of marine origin occur above and below most of the beds. There must have been more than 20 advances and retreats of the sea in such a region.

The total coal reserve still underground in the Pennsylvanian rocks is vast, but it is not inexhaustible and the more easily obtainable coal is being rapidly mined. About 545,000,000 tons of coal per year are mined from Pennsylvanian rocks. The leading producing states and the amounts produced are given in the table on page 374.

In general the coal from the western part of the area is poorer than that from the eastern; the change is fairly gradual and constant westward, save that the anthracite is confined to one area and the change to bituminous is abrupt.

For the last century coal has been the most important mineral product of the world and no nation reached industrial supremacy without access

Rank	State	Tons, 1933	Rank	State	Tons. 1933
1	Pennsylvania	130,000,000	9	Tennessee	3,570,000
2	West Virginia	90,770,000	10	Missouri	3,432,000
3	Illinois	36,110,000	11	Iowa	3,230,000
4	Kentucky	35,530,000	12	Kansas	2,160,000
5	Ohio	19,960,000	13	Arkansas-Oklahoma	2,170,000
6	Indiana	13,500,000	14	Maryland	1,500,000
7	Alabama	8,775,000			
8	Virginia	8,390,000			

to large supplies of it. Most nations have guarded their supplies with great care, but the United States has always been prodigal of all of its natural resources and not until within the last few years has it made any effort to conserve them. Coal was mined in such a manner as to leave quantities underground that can never be recovered, and a great deal of that mined was wasted. Some restrictions are needed. Such restrictions necessarily increase the price of the product but the increase is not large and the people of a nation should be glad to help in conservation to prevent deterioration and conserve for posterity. Conservation could be attained by the use of more efficient engines. The average engine which uses coal for fuel gets only about 20 per cent of the power that might be obtained from the coal; 60 per cent would reduce the consumption of coal to less than half what it is today, as about three-fourths of the coal consumed is used in engines of various kinds. The United States produces more than half of the coal of the world but exports little.

The question is often raised whether coal is forming at the present time. The answer is in the affirmative, but it is forming in only small areas and in small amounts. If one considers that the Pennsylvanian coal was at least 10,000,000 years in forming with one-fourth of the United States under swamps, he will see that the rate was very slow. Vegetation is not accumulating today as coal fast enough to keep one big factory running.

Oil and Gas.—Since the invention of the internal-combustion engine such as is used in the automobile, petroleum has come to compete with coal as a producer of power and many industries are directly dependent on petroleum for their existence. Within the last 20 years the world production of petroleum has increased from about 300,000,000 barrels per year to over 1,400,000,000 barrels. This has raised the production and refining of petroleum to one of the big industries.

The Oklahoma-Kansas oil field has long been the most important in producing petroleum for the manufacture of gasoline, and up to 1927 almost the entire production came from Pennsylvanian rocks. While the areas east of Oklahoma were swampy land a sea extended northward from Texas through Oklahoma and Kansas into Nebraska. The sea was

shallow and abounded in animal life and petroleum formed in it in great quantities. The rocks consisted of limestone, sandstones, and shales in alternating beds. Oil formed in shales and limestones and migrated into the sandstones. During the Permian low folds formed in the rocks of Oklahoma and Kansas (at about the same time that the Appalachian Mountains were forming) and the oil migrated into the anticlines, from which it is obtained today.

Almost incredible amounts of oil are obtained from some wells and from some areas. The largest well ever brought in in the midcontinent field made about 140,000 barrels per day, but most wells make a few barrels to 5,000 barrels per day. A vast number of anticlines have been drilled in Oklahoma and Kansas and nearly all of them produced oil. This is a high average, as not more than about one-fifth of the anticlines of the United States have produced even where all conditions seemed favorable. The Pennsylvanian produces from many beds in the same field and that accounts for the production from almost every anticline in the field.

The production from the Oklahoma-Kansas field has averaged about 300,000,000 barrels per year for the last 5 years. The oil is of high grade although not so high as the oils from Pennsylvania and West Virginia that come from older rocks. The age of the rocks which produce petroleum seems to have little to do with the grade of oil produced. In some places high-grade oil is produced from younger strata and deeper drilling gets low-grade oil from the older rocks, while in other fields the reverse is the case.

There is a general idea that oil is in some way associated with coal and occurs only where coal beds are present, but oil and coal have no necessary relationship. Some of the largest oil fields have no coal and many of the largest coal fields have no oil. The two are formed under radically different conditions, oil always associated with bodies of still water, usually the sea, and coal with swampy conditions. Oil is not always associated with salt water in the wells although some not familiar with oil production think that the finding of salt water in a well indicates that oil will be found and that the absence of salt water presages absence of oil. No particular kind of topography indicates the presence or the absence of oil. Many drillers believe that geologists are likely to locate their wells in the worst possible area for the convenience of the driller, but as a matter of fact the geologist pays no attention to the convenience of the driller in getting in his machinery until after the anticline has been mapped. He then makes the most favorable location for a test well and that may be on the top of a hill, in a valley, or on a steep side of a hill (Fig. 353).

As stated in another paragraph, producers are drilling to the Ordovician rocks to keep up the production in the midcontinent field and the Penn-

sylvanian rocks are nearing exhaustion of their supply. No doubt, some new fields will be developed in the Pennsylvanian of the Oklahoma-Kansas field, but it seems clear that the greater part of the oil has been taken out.

The question might be raised as to why drilling to the Ordovician is necessary rather than stopping in some of the rocks between the Pennsylvanian and the Ordovician. The Mississippian rocks are mainly limestones and did not have enough sediments deposited with them to hold the oil if it formed. Also, the water may have been too deep for the formation of the oil and the retaining of it. The Devonian rocks of the region are absent or too thin to have accumulated much oil. Even if oil formed in them as they were being deposited they were so deeply eroded before the Mississippian that all of the oil would have escaped. If oil is trapped in rocks and streams cut through the overlying impervious strata all of the oil finally escapes. The Silurian rocks are absent in some places, too thin in others, and not of the right kind in others. Where the rocks of a period are all sandstone oil will not occur unless it migrates to the sandstone from other rocks and has been covered by impervious rocks of a younger period.

Clay.—Clay for the manufacture of brick, tile, and pottery comes from the Pennsylvanian shales, and fire clay, a clay used in making brick for furnace linings and other things requiring resistance to great heat, occurs associated with coal in many places. The clay industry is a very large one but the value of the material comes largely in the manufacturing; the raw product is not of such great value.

Iron.—A great deal of iron was deposited in Pennsylvanian bogs in the same place as the clays. Most of it is of low grade and will not be mined until the high-grade ores of other periods are exhausted.

PRODUCTS OF THE PERMIAN

A decade ago the Permian was considered one of the least important of all of the periods in economic products, but later knowledge has changed its status to a considerable extent. In Wyoming the oldest oil field was developed in Permian rocks but it was small and of little consequence. Captain Bonneville, whom Irving made famous in his book of that title, camped near an oil spring not far off the old Oregon trail and recorded the presence of the oil spring in his journal. In 1883 a well was drilled on the site of the spring and black oil was obtained from the Permian rocks. The field is still producing and one of the wells drilled 35 years ago is still flowing. Figure 352 shows one end of the anticline.

In 1928 a 75,000-barrel well was drilled in western Texas and the Permian rocks furnished the oil. Many large wells have been drilled since, and the Permian promises to become one of the largest producers of oil in the United States.

In southeastern New Mexico and southwestern Texas are the largest salt and gypsum deposits of North America, but they are not of commercial importance at present as neither is mined. The size of the deposits is known from wells drilled into them in many places. The last deposits of Permian seas that were drying up were potash salts. Permits have been taken by several companies looking toward commercial production of the potash as fertilizer.

In Wyoming, Montana, Utah, and Idaho are extensive phosphate deposits that form a potential source for fertilizers. Fertilizers must come to be used more extensively as soils wear out. The phosphate is being mined in only one place at the present time and in very small quantity. The government has withdrawn most of the phosphate areas from homestead entry and the deposits will finally be leased to producers.

Although potentially the Permian contains mineral deposits of great value, at present its production is small.

CHAPTER XXII

THE MESOZOIC ERA

The word Mesozoic means middle life and suggests life midway from its origin to its present condition. The term is only relative as the era is far beyond the middle of geologic history and animals and plants had progressed much beyond the middle in the evolutionary scale. However, the term is a good one as, in general, it connotes the situation correctly. The Mesozoic was not nearly so long as the Paleozoic and it is divided into only three periods, Triassic, Jurassic, and Cretaceous, possibly 150,000,000 years in all. The same principles apply in the division into periods as are used in the Paleozoic.

When the Paleozoic closed with the uplift of the North American continent and the formation of the Appalachian Mountains, there seems to have been no sea left over any part of what is now the land of North America. All was exposed to erosion and was deeply eroded in many places before the readvance of seas.

Causes of Sea Advances.—It may be well to recapitulate the causes for advancing of the seas before taking up the physical history of the Mesozoic. First in order is the down-warping of the land or the up-warping of the sea basin. Down-warping of the land allows the seas to come in locally over the areas affected, while up-warping of the sea basin causes general sea advance. The second cause is the down-cutting of the land by streams and other agents, which may bring it low enough to allow the seas to advance with very little rise of sea level. The third cause, the filling of the seas by the piling up of sediments in them as streams carry the materials from the lands, goes along with the down-cutting. These are cumulative, as both the cutting down of the land and the piling up of the materials in the seas cause smaller differences between depth of sea bottom and height of land.

The Mesozoic-Paleozoic Boundary.—As the Mesozoic-Paleozoic boundary is one of the most important in the geologic column, one would expect to find a plainly evident physical break there. In order to get first-hand information about the boundary geologists go to a place where it is exposed, the rocks of the Mesozoic resting directly on those of the Paleozoic. In eastern North America there is no place where oldest Mesozoic rocks rest on youngest Paleozoic. No rocks of the first part of the Mesozoic are present in or east of the Appalachian Mountains and none of latest Paleozoic. One must go as far west as the Wasatch Mountains to find the contact of oldest Mesozoic on youngest Paleozoic.

From what we have learned of geologic history and of Paleozoic rocks, have we anything definite to anticipate about the contact? We know that the Paleozoic closed with the folding of the Appalachian Mountain region and general uplift of the entire continent. Erosion was in progress on the entire continent for some time before seas came in again over the land. The first of the Mesozoic sediments would be deposited on rock surfaces produced by erosion, but on what kind of rocks? Are the Paleozoic rocks different from the Mesozoic? In anticipating the appearance of the contact we should remember that the Mesozoic rocks

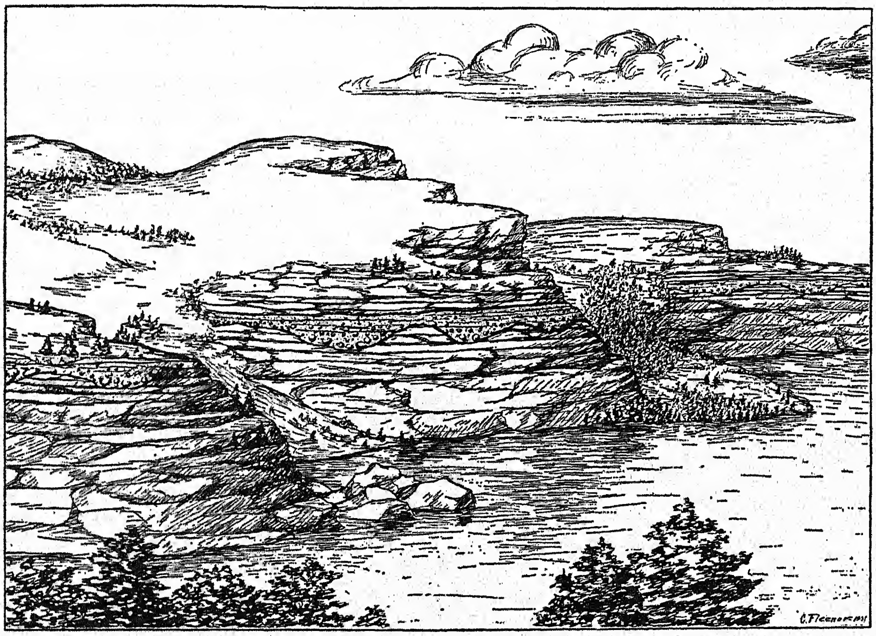

FIG. 385.—Contact between Paleozoic and Mesozoic rocks where the Paleozoic rocks are horizontal.

were deposited millions of years ago and all have been subject to pressure and cementation, some to deformation and metamorphism.

The contact in the Wasatch Mountains shows nothing very striking and expert geologists might pass it many times without finding it. Both Paleozoic and Mesozoic consist of formations of shale, sandstone, and limestone, and the kind of rock gives no clue to the place of contact. In this region there was no deformation of the Paleozoic beds before the Mesozoic seas came in and the Mesozoic beds are parallel with the Paleozoic. Erosion had not greatly roughened the surface of the Paleozoic rocks, and the slightly irregular surface on which the oldest Mesozoic sediments were deposited is not apparent in most places even where erosion has exposed the contact. The fossils in the rocks are the only means

of determining the contact, and the Wasatch Mountains' section fails the geologist in that the lowest Mesozoic rocks are nonfossiliferous.

In many places in the Rocky Mountains a red sandstone overlies limestone that contains Permian fossils. Near the bottom of the sandstone one bed contains Mesozoic fossils, and on that account the line of contact is drawn at the base of the red sandstone. The fossils are indicative of the age of the rock and the change from limestone to red sandstone shows marked differences in physical conditions under which the rocks formed. After long investigations in the field an unconformity was detected at the base of the red sandstone, and it helps to fix the place of contact.

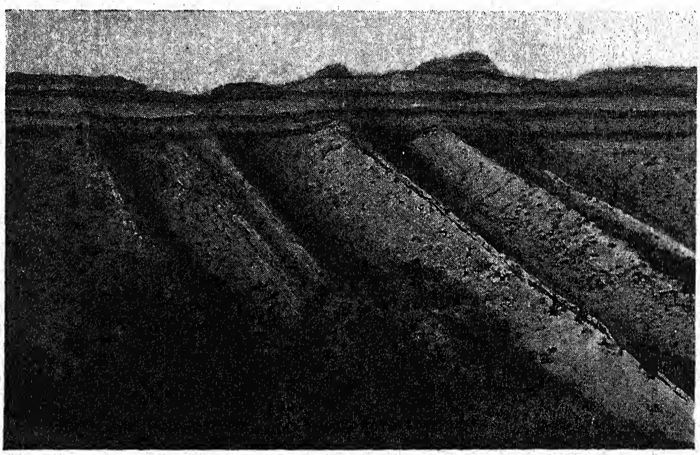

FIG. 386.—Unconformity at the Paleozoic-Mesozoic boundary. (Horizontal Mesozoic beds drawn in above dipping Paleozoic beds.)

If one could find a place where the latest Paleozoic rocks had been folded and eroded before the early Mesozoic rocks were deposited, the contact would appear definite and unmistakable, although it could not be identified as the Paleozoic-Mesozoic boundary without determining the age of the rocks both above and below the unconformity by the fossils in them (Fig. 386). Such a contact would suggest larger changes than those separating one period from another.

The changes in animals and plants from late Paleozoic to early Mesozoic were the largest recorded in geologic history from one period to the next succeeding, and the differences in fossils first gave rise to the era division. Geologists are accustomed to finding fossils of one period definitely related to those of the preceding, but early Mesozoic forms are so different from late Paleozoic that they might almost belong on another planet. In order to bring about such changes in the life there must have been events as revolutionary in other parts of the earth as the elevation and folding of the Appalachian area in eastern North America.

CHAPTER XXIII

TRIASSIC, OR LOWER MESOZOIC

The Triassic, the oldest period of the Mesozoic, was named from its threefold development in the Alps. No such development occurs in America, and the history of the period was strikingly different from that in Europe, and its record is far less complete.

First Advance of Seas.—The highlands at the close of the Paleozoic were of sufficient extent to keep the seas from any considerable area of the continent for a long period of time, and prevented large invasions except in places where marked down-warping took place. It is not surprising that the first sea invasions were small, and as the Appalachian Mountains had formed near the Atlantic Coast it was to be expected that the earliest sea advance would not be on that coast. During the first period of the Mesozoic the seas did not advance either on the Atlantic Coast or the Gulf Coast, but all invasions were from the Pacific. At first they spread over a very narrow margin of land near the present coast and gradually crept in farther and farther. Although there were no mountains in the Pacific region, there were low ranges of hills and highland areas that caused irregular distribution of the seas. Near eastern California a range of hills restricted the sea advance, but valleys through the hills or gaps in them finally allowed the waters to spread eastward into the area of the present Rocky Mountains and Great Basin[1] (Fig. 387).

Formation of Red Beds.—From some source this region was supplied with red sand, and the sandstones, generally designated as the red beds, were deposited over an area stretching from central Montana to central New Mexico and from eastern Colorado to Nevada. The red sandstones are the most striking, though not the most widespread, of the Mesozoic formations of North America. Along with the sandstones red shales were formed and in many places gypsum was deposited. The gypsum deposits indicate aridity of climate while they were forming. Red sediments may also indicate aridity of climate, but, on the basis of red color alone, aridity should not be inferred. West of the hills that restricted the Triassic seas no red beds were formed although the area seems to have been under the sea during most of the Triassic. In California and western Nevada the deposits were mainly limestones. The near-shore phases were conglomerates and sandstones, and offshore deposits included much shale. No Triassic rocks are exposed between

[1] Geologists are not in agreement on the extent of Triassic seas.

the Rocky Mountains and the Appalachian Mountains except in the Black Hills region, and it is probable that none were formed except in the vicinity of the front ranges of the Rockies.

Brown Sandstones.—In the late Paleozoic, synclines, anticlines, and faults, originating at the same time as the Appalachians and running

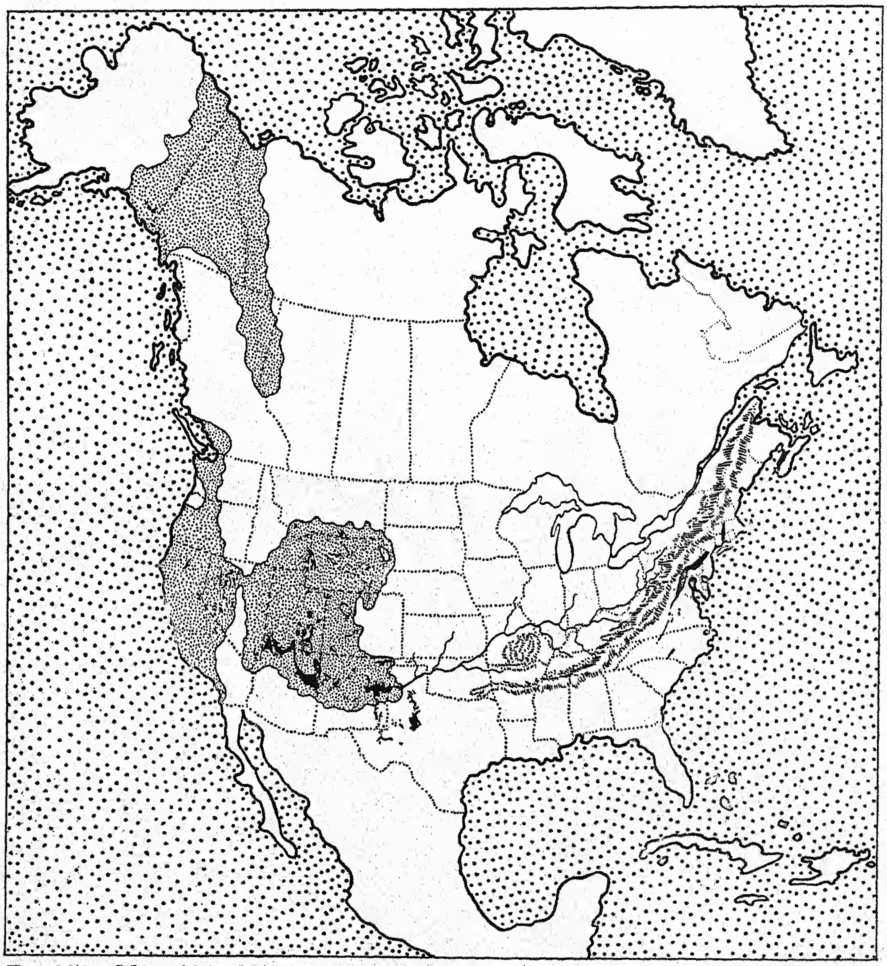

FIG. 387.—Map of North America; Triassic epicontinental seas in fine stipple, outcrops in black.

parallel to them, formed eastward of them as far as the present coastline. So far as is known, none of the synclines was below sea level during the Triassic, but they were the sites of rivers and lakes and in them alluvial fans and flood-plain deposits formed, similar to those now forming in the Great Valley of California. In some places the intervening hills were high and coarse materials were washed into the valleys. The streams

were vigorous and deposited sand and gravel more extensively than the finer materials. Brown shale, sandstone, and coarser materials were deposited in the old synclines from northern Massachusetts to North Carolina (Fig. 387).

Many buildings in New York, New Haven, and other cities near or on the Triassic deposits were built of what was called the Connecticut brownstone before it became cheaper to build of brick and the fashion in stone changed. The brownstone fronts were once the most aristocratic dwellings of New York City; great rows of brownstone buildings may still be seen, although they have now become poor class and are rapidly being replaced by more modern brick buildings.

The eastern Triassic rocks are red or brown, but no gypsum is associated with them and the climate was not arid. Moist climate is indicated by coal deposits of Virginia and North Carolina. Coal from these beds was the first to be mined and used in the United States.

Volcanism.—In New York, Massachusetts, and New Jersey the period was one of great igneous activity. In the Connecticut Valley, lavas were extruded into a large syncline, were covered later by sediments and in turn by more lava. Lavas issued through fissures and spread out laterally as sills, but in most cases the flat-lying lava bodies, represent lava flows rather than sills or other lava intrusions. Much faulting took place in the synclines, and in many cases the faults furnished the conduits through which the lavas issued.

The Hudson River in its lower course cuts through some of the old lava flows where they had formed columnar structures on cooling. The Palisades along the Hudson are made up of vertical prisms of basalt which may be clearly seen for long distances. The Triassic igneous rocks are mainly basalt and were extruded or intruded near the close of the period.

Distribution.—By examining the map of the Triassic outcrops you will see that they cover only small areas compared to those of most Paleozoic periods, and that the general distribution is greatly different from that of Paleozoic periods.

LIFE OF THE TRIASSIC

The greatest known break in life, or perhaps it would be more accurate to say the greatest known changes in life, are those of late Paleozoic and early Mesozoic, often spoken of as coming between Paleozoic and Mesozoic.

Invertebrates.—In general the invertebrates were the most important animals of the Paleozoic while the vertebrates were the most important of the Mesozoic. Four classes of invertebrates of the Paleozoic were considered particularly, for the reason that they were highly characteristic. Trilobites were abundant in early Paleozoic, but no specimen has ever been found in a Mesozoic rock. The brachiopods, although

abundant to the close of the Paleozoic, became so rare that one may collect in Triassic rocks that are highly fossiliferous for many days without finding a specimen. Fossiliferous Paleozoic rocks are characterized by the presence of either trilobites or brachiopods or by both, whereas fossiliferous Mesozoic rocks are characterized by the absence of trilobites and the rarity of brachiopods. Another group of invertebrates by which Paleozoic and Mesozoic rocks may be distinguished is the cephalopods. They are common ~~in the Paleozoic from~~ the Ordovician onward and they are one of the most important forms in the Mesozoic. The cephalopod has a chambered shell, but the partitions between the chambers of most Paleozoic cephalopods were simple, whereas in the Mesozoic they were exceedingly complex. The differences between the two are indicated in Fig. 388. The presence of very complex partitions, which are indicated on the outer side of the shell by sutures, is sufficient to determine that a rock is Mesozoic rather than Paleozoic.

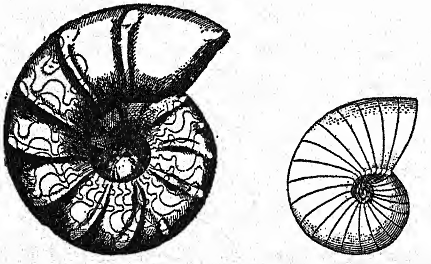

FIG. 388.—A Paleozoic cephalopod with simple sutures at the right. (*From Texas Geological Survey.*) A Triassic cephalopod with complex sutures at the left. (*From J. P. Smith.*)

In California, Nevada, and Utah the first seas of the Triassic brought in great numbers of the complex sutured cephalopods. In places the rocks were almost entirely made up of them and throughout the period they were the most abundant animals. However, east of California and Nevada they did not last beyond the lower part of the Triassic. When the red sandstone and gypsum of the Rocky Mountain and Great Basin regions began to form, the cephalopods either emigrated or perished and in the major part of the great series of red beds no cephalopods have been found and only very few other marine invertebrates were present.[1]

The crinoids are one other group of invertebrates of which some Paleozoic rocks are almost entirely composed. Crinoids became very rare in the Mesozoic and are practically absent from Triassic rocks.

The clam group (pelecypods) was abundant from Ordovocian to the end of the Paleozoic. They formed an important part of Mesozoic fauna but were rare in the Triassic.

Vertebrates.—Although it may not be possible for us to arrive at any appreciation of the real differences between the invertebrates of Paleozoic

[1] The absence of marine invertebrates from the red beds has led many students to believe that the formations are continental in origin rather than marine in spite of the extensive gypsum deposits; and although geologists are agreed that large parts of the red beds are marine, some contend that considerable parts are continental and all believe that the parts that bear fossils of land vertebrates are mainly continental.

and Mesozoic, we can see the differences between the vertebrates, because we are more familiar with vertebrate animals. The oldest vertebrates, the fishes, were first represented in the Ordovician period of the Paleozoic. In the Devonian came the amphibians, which were capable of breathing air and had developed walking legs and higher organization than fishes. In the Pennsylvanian reptiles appeared, and in the Permian they became rather abundant in some areas although all of them were of groups which did not survive. The Mesozoic is known as the Age of Reptiles, and properly so, although the history of the reptiles of the Mesozoic is still imperfectly known.

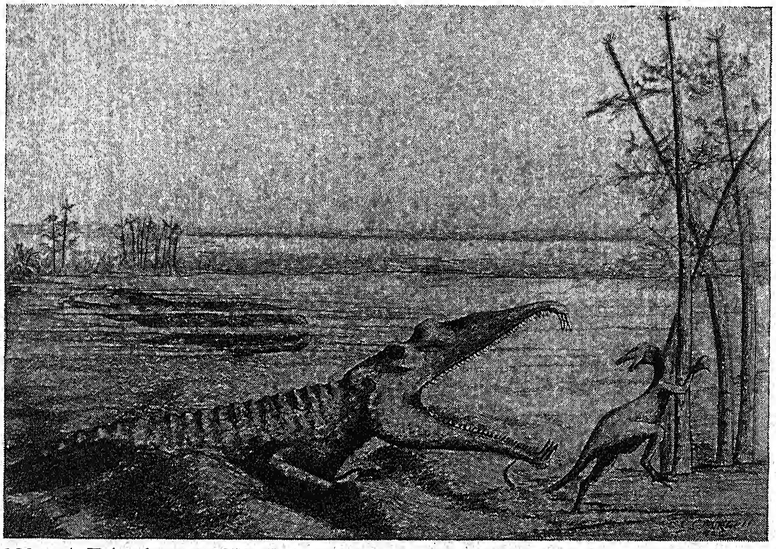

FIG. 389.—A Triassic crocodile-like reptile chasing a small dinosaur. (*From M. G. Mehl.*)

Reptiles of Western North America.—The oldest reptiles known from the Mesozoic of North America were found in the red beds of the Rocky Mountain region and are about middle Triassic in age. The number of kinds of these reptiles is small compared to the number present in late Paleozoic, and nearly all belong to a crocodile-like group (Fig. 389). In form they resemble the long-snouted crocodiles which now inhabit the rivers of southern Asia. Several different kinds that lived during the middle and upper Triassic left their remains in the western red beds, and they were probably rather numerous in the rivers. Some remains of other kinds of reptiles, (one a small dinosaur) have been found in the red beds, but they make up an unimportant part of the total and need not be considered at this place.

Amphibians of Western North America.—Large amphibians were rivals of the reptiles for the supremacy of the lands and rivers near the

western seas. Some of the amphibians were 8 or 10 feet long and were the largest of their kind that ever lived in America. Some of them had heads more than 30 inches long by 18 inches wide. They were the last of the old types of amphibians and their place was taken by the toad and salamander types in later periods. They were clumsy, slow-moving creatures and their bulk alone enabled them to compete with the reptiles. They were heavily armored on the ventral surface of the body but the

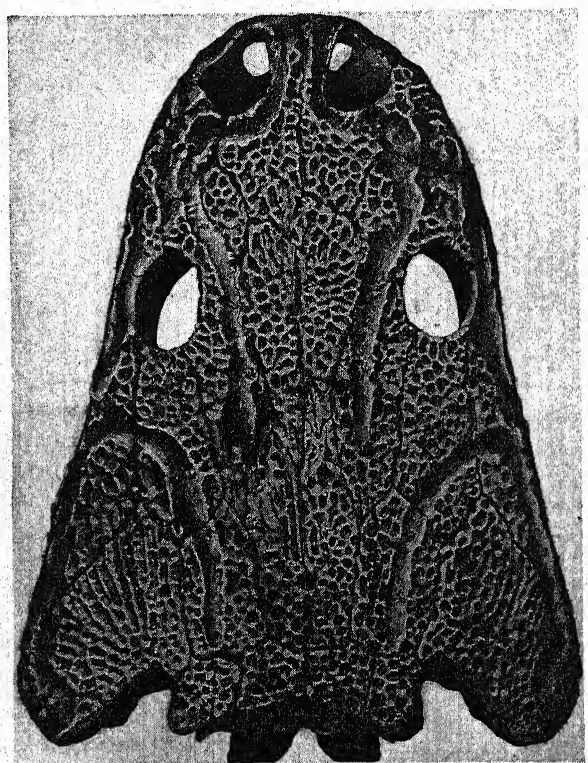

FIG. 390.—Skull of a large Triassic amphibian. The animal was probably more than ten feet long.

armor was of little use to them as a protection from the reptiles as they were unprotected on the back. Perhaps the Triassic rivers of the west might be compared with the upper reaches of the Congo River of the present—the crocodiles there representing the reptiles; the hippopotami, the amphibians. Such a comparison is for numbers and sizes only as the amphibians are not related to the hippopotami. However, one who has seen pictures of the life of the upper Congo might replace the huge, clumsy mammals with amphibians of much the same size, but much lower, and thus get a living picture. The crocodilians were smaller than those of the Congo and were not of such voracious kinds. The resemblance

ends with the two kinds of animals as other kinds were absent or very rare.

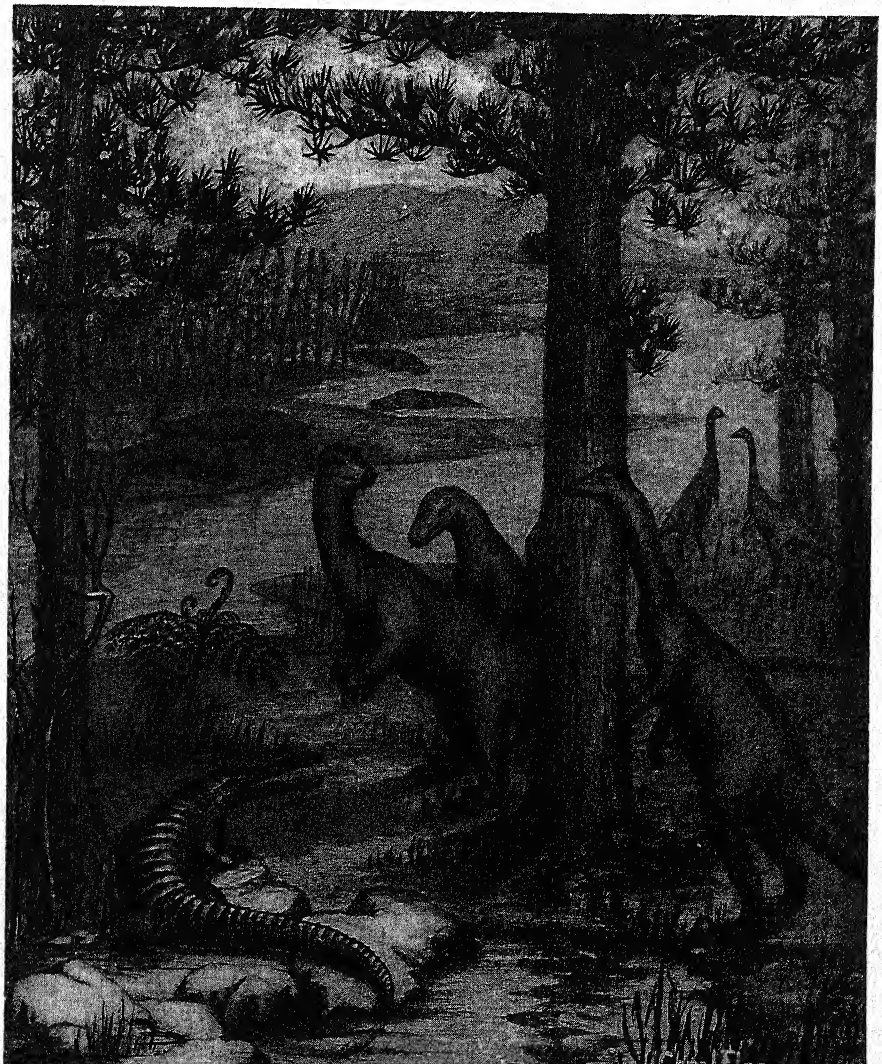

FIG. 391.—A general assemblage of Triassic reptiles and amphibians. The animals in the background are amphibians, the five animals walking on their hind legs are dinosaurs, the animal in the left foreground is a primitive crocodilian.

Faunas of Eastern North America.—The best representation of Triassic land life in any part of North America is from the deposits in the old synclines in Connecticut. The same type of crocodile-like animals as in the west were present here but they were not the most important forms. Another group, destined to become the most important of the

Mesozoic, the dinosaurs, had made its appearance. Tracks were the first fossils of the dinosaurs in the Connecticut Valley to attract attention. Some of the sandstone surfaces there are marked with a complete network of tracks of various sizes and kinds. These were called bird tracks, or more specifically, turkey tracks, when they were first found, and a book was written on the bird tracks of the Connecticut Valley. The tracks look like those made by birds, and many of them were made by three-toed animals that walked on only two legs. The number of kinds of tracks is much greater than the number of kinds of bones that have been discovered, but many kinds of dinosaur bones have been collected

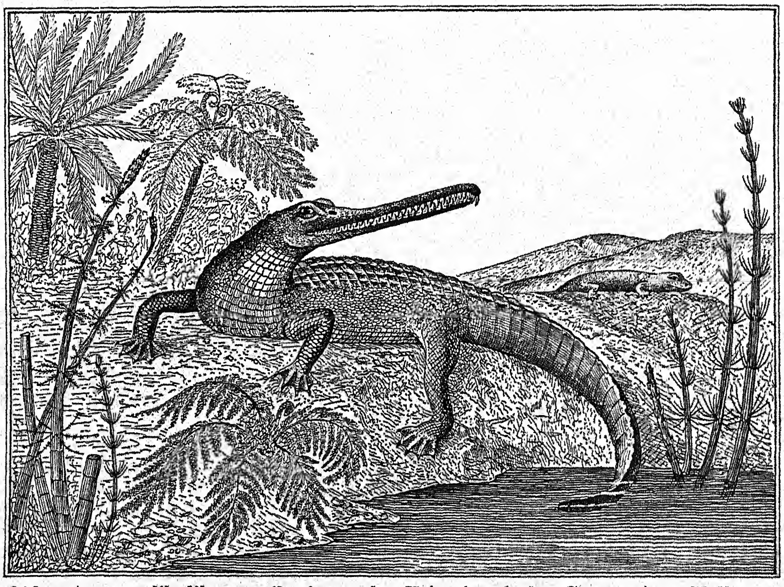

FIG. 392.—A crocodile-like reptile from the Triassic of the Connecticut Valley. (*An unpublished drawing by Williston.*)

and the peculiarities of the animals worked out. The rarity of the bones was such that at first they were collected no matter what the difficulty. It is told of Professor O. C. Marsh of Yale College that on finding dinosaur in the rocks of a bridge he succeeded in having the bridge torn down so that he might get the bones.

Although some of the dinosaurs were larger than horses, none of them reached such a size as to suggest that their descendants were to be the largest of all land animals. At this early stage they had begun to show a varied and striking development. Some were carnivorous, with long, strong teeth while others were strictly herbivorous. Some were quadrupedal while others had the fore feet reduced to small size, walked on strongly developed hind legs, and dragged a heavy tail which balanced the body. Some had solid, heavy bones while other had hollow, light

bones and were agile jumpers. If one could have observed the life in the Connecticut lowlands he would have been struck by the great variety in kinds of land animals of conspicuous size.

Amphibians similar to those of the west but smaller were present in the Connecticut Valley.

Swimming Reptiles.—It seems that the time of great variation in reptiles had a second wave, the first coming in the late Paleozoic, the

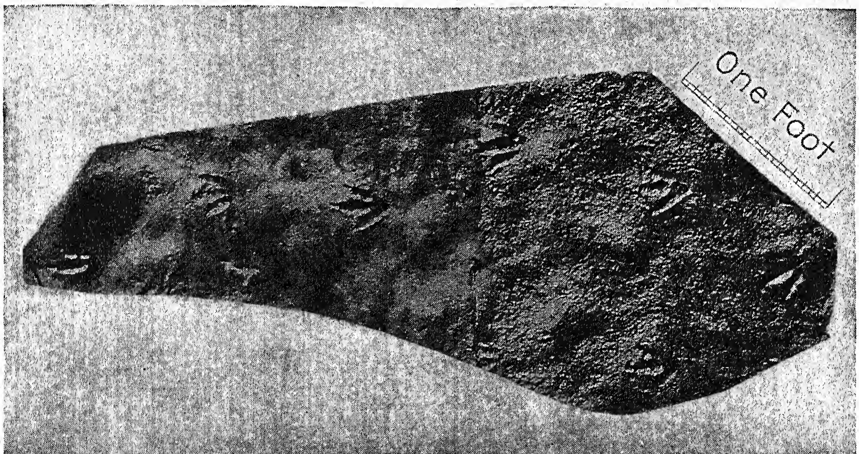

FIG. 393.—Dinosaur tracks from the Triassic of the Connecticut Valley. (*After Moore.*)

second in the first period of the Mesozoic. In central Europe and far-western North America the developing reptiles lived near the sea margins, and it is not strange that some of them became good swimmers and finally took up their habitat in the seas. This was true of two large orders of reptiles which originated during Triassic time. Both developed paddles instead of feet and were good swimmers, but in other respects the orders were decidedly different. One order, the ichthyosaurs, had a very short neck and a long tail which was its main swimming appendage. Its front paddles were very large, its hind paddles small, its eyes very large, and its snout long and slender.

FIG. 394.—A swimming reptile, Ichthyosaur, from the Nevada Triassic, about $\frac{1}{40}$ natural size. (*After Osborn.*)

Flying and Other Reptiles.—While the water afforded one habitat in which great specialization could take place, the air furnished another, and flying reptiles in primitive, poorly developed form appeared during the Triassic. These will be described more fully in Jurassic and Cretaceous faunas. Primitive forms of such modern reptiles as lizards and turtles also made their first appearance in the Triassic. Several other orders which are not important enough for us to consider here, also appeared.

This was a time of great variety of specialization and of appearance of numerous new forms. At such times the origin of strikingly different forms may be expected, and it was here that the culmination of animal life, the mammals, made its appearance.

Appearance of Mammals.—The change from some highly specialized reptiles to lower types of mammals was not very large. Differences between the two as to the skeletal framework, *i.e.*, the bones, are small and experts disagree as to what these differences really are. One rather pronounced difference between mammals and reptiles is in the teeth, which are differentiated into incisors, canines, and molars in mammals but not in reptiles. The lower jaw of reptiles articulates with a bone in the skull called the quadrate (Fig. 395). No quadrate is present in mammals and the jaw articulation is quite different. The reduction and disappearance of the quadrate bone and the differentiation of the teeth

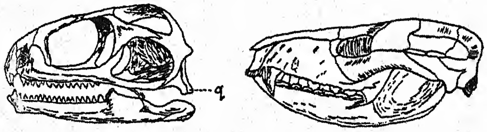

Fig. 395.—Skull of an early mammal on the right, and of a reptile on the left. The quadrate bone (*q*) present in the reptile skull is absent from the mammal skull.

into incisors, canines, and molars may be considered as transitional stages from reptiles to mammals. Both of these occur in one group of Triassic reptiles in South Africa.

We readily tell the difference between mammals and reptiles by the former having the body covered with hair and the latter being covered with scales or bare, also by the mammal suckling the young and the reptile feeding the young in other ways. There are several anatomical differences in the soft parts and embryological differences, but the geologists can find no evidence on the time of origin of hair, of the suckling of the young, or of the embryological differences, as none of them is preserved in the fossil state. Fossils furnish evidence only of changes of the skeletal parts.

The appearance of mammals would have seemed to be of little importance if one could have observed this appearance and known the details. Throughout the Mesozoic, mammals were small, rare, weak, and seemed to have little chance in competition with the reptiles. One might as readily predict that some rare small form of the present, say like the anteater, would finally give rise to the rulers of the earth, as to have said in Mesozoic times that mammals were the coming rulers.

Plants.—One of the striking curiosities for tourists who travel through western United States is the numerous petrified forests. Those of Arizona are well known and most of them are in Triassic red beds. Trees are preserved in great numbers and are of large size. The trunks

are silicified and the silica is of many colors giving a striking appearance to the petrified wood. In the main petrified forest thousands of the trees have weathered out of the rock and lie scattered over the clays and sands of the red rocks. As they are much harder than the rest of the rock they remain behind after it has been eroded away. Trunks of trees 3 feet in diameter and 100 feet long have been found. Petrified forests in the Triassic are also rather common in New Mexico, Colorado and Utah, and petrified wood is abundant in Wyoming. A peculiarity of some of the petrified forests is that the trees have no bark. They seem to have been transported for long distances and to have had the bark worn off in transit. Modern flowering plants had not appeared and the trees were not greatly different from those of the Paleozoic.

FIG. 396.—Fossil tree trunks from the Triassic of Arizona forming a natural bridge. (*Photograph by Willis T. Lee, courtesy of U. S. Geol. Survey.*)

MISCELLANEOUS

Climate.—The cold late Paleozoic climates had given place to warmer, and before the middle Triassic warm climate prevailed over most of the earth. Lower Mesozoic rocks are not known in many places in high latitudes, but in Spitzbergen, at 75° north latitude, the animal and plant life was much like that in southern United States. Reptiles and amphibians flourished there, and they cannot survive in very cold climates, as they are cold blooded, *i.e.*, their blood takes on the temperature of the surrounding medium. Rings of growth were not present in the Triassic trees, indicating absence of seasonal changes of climate. Gypsum deposits point to aridity in parts of the Rocky Mountain region, but arid conditions were local. The presence of large petrified trees points to abundant rainfall, but the trees may have grown in higher, more moist regions, and have been transported to the lower, arid places.

Economic Products.—The Triassic furnishes the least important economic products of any period thus far considered. The brownstones of the eastern deposits, the coal of North Carolina and Virginia, road metal from the igneous rocks, and the gypsum of the Rocky Mountain region constitute the very small list. Although gypsum occurs in great quantities it is used very little.

Close of the Triassic.—No large continental movements took place to bring the Triassic to a close. The seas gradually withdrew until no marine areas were left on the continent of North America.

CHAPTER XXIV

JURASSIC, OR MIDDLE MESOZOIC

The term Jurassic was derived from the Jura Mountains between Switzerland and France, where rocks of the period are well exposed.

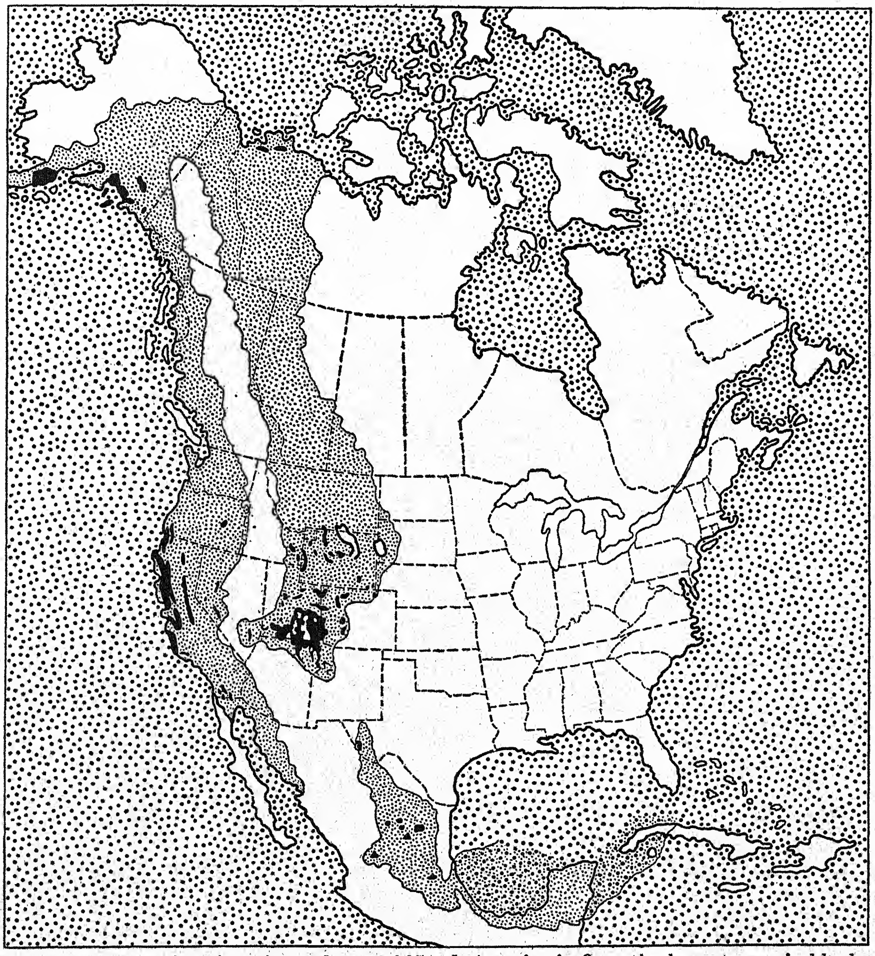

Fig. 397.—Jurassic epicontinental seas of North America in fine stipple, outcrops in black. (*Seas modified from Schuchert.*)

In North America the seas advanced only from the Pacific Coast during the early part of the period and spread eastward to eastern California.

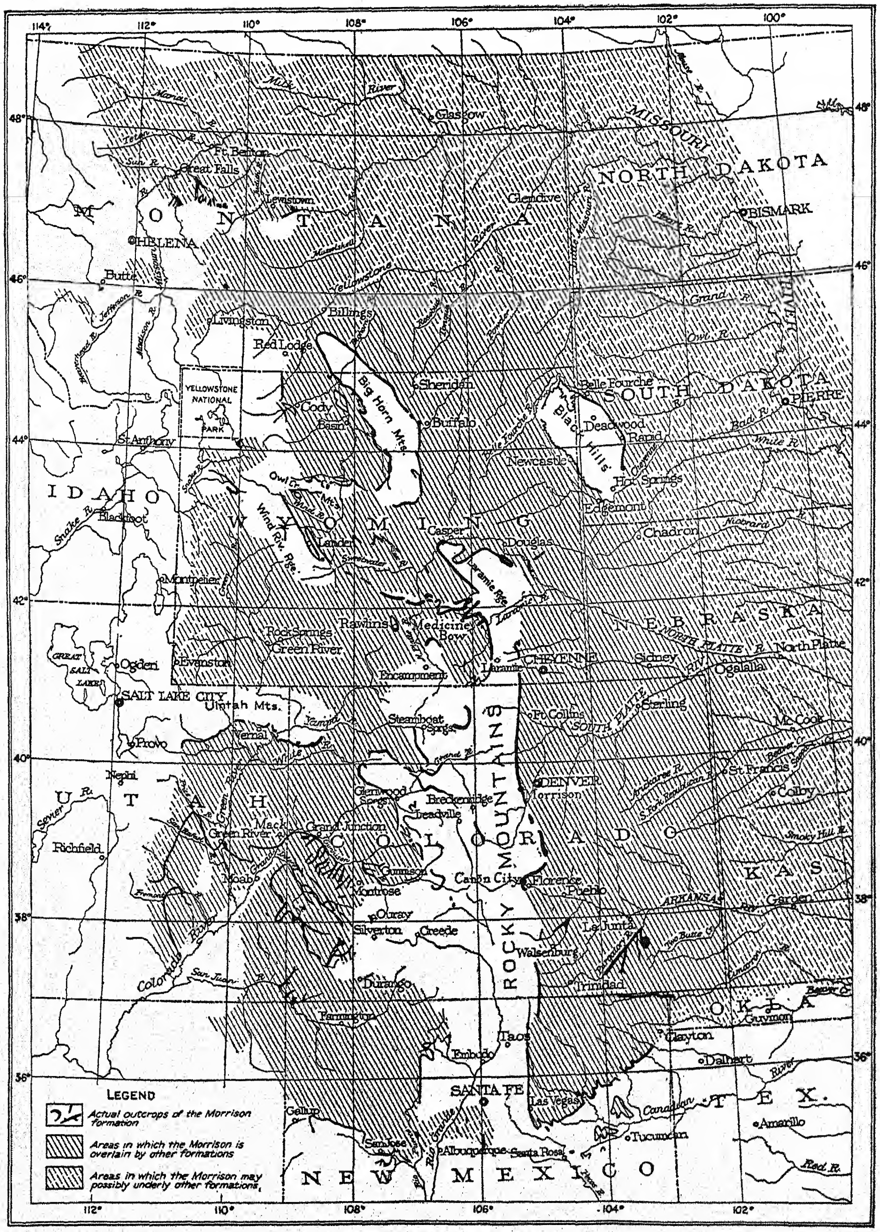

FIG. 398.—Map showing areas of outcrops of the Morrison formation. (*After Mook.*)

Later a sea advanced from the Gulf of Mexico, through Texas, Mexico, and New Mexico. Still later an Arctic sea transgressed southward through western Canada into Montana and Wyoming and as far south as central Colorado. There were no Jurassic seas in the eastern part of the continent. This is the only period of geologic history in which no deposits are known east of the middle of the continent.

All Jurassic seas excepting those near the Pacific coast were short-lived, and the deposits in them were thin, not ranging above 400 feet in most places. You can see that a thin deposit formed in a sea such as advanced from the Arctic must consist quite largely of sediments deposited as the sea was advancing and while the sea was retreating, and that they would be made up largely of sands, gravels, and clays. Also, if the seas were shallow, sediments would not be well sorted as materials after settling to the bottom might be disturbed by storm waves and mixed up with other materials, sands with clays and pebbles with sands. Limestones would have little chance to form where the storm waves struck the bottom, and although lime might be deposited on the bottom, large storms would create waves that would mix the lime with sand and clay. In some places in Montana, Wyoming, Utah, Colorado, Idaho, and British Columbia the seas were deep enough to permit limestones 40 to 50 feet thick to form over large areas.

Morrison Formation.—In the Rocky Mountain region the formation called Morrison has long been under discussion as to whether it is Jurassic or Cretaceous. While the authors recognize the controversial nature of the subject, the formation will be called Jurassic in this text. The Morrison overlaps the marine deposits formed by the sea that came in from the north and lies unconformably on them. The extent of the Morrison is shown in Fig. 398 and it is worthy of consideration because of the fossils it contains. Presence of large numbers of land fossils, poor bedding, poor sorting of materials, lack of marine fossils, loess deposits, and dune deposits indicate that it was continental in origin. Great variety of coloring ranging through blues, greens, yellows, reds; colors not confined to particular beds but crossing from one to another; and many pieces of wood in various beds are contributing evidence of origin.

LIFE OF THE JURASSIC

Marine Invertebrates.—The life in the Jurassic seas shows general development from that of the Triassic. In North America the seas were not so dominated by cephalopods as in the preceding period. Fewer fossils are known from the Jurassic of America than from any other period; this is directly opposite to the condition in Europe, where Jurassic fossils are very abundant. Oysters and other pelecypods and a new type of cephalopod with an internal shell that looks like a slender cigar were common in the North American seas.

Dinosaurs.—The main interest in Jurassic life in America is in the land vertebrates, and all of these are contained in the Morrison formation. The abundant fossils in the Morrison are dinosaurs. More dinosaur remains have been collected from it than from all other formations in America and more than from any other formation in the world. In March of 1878 three men independently discovered dinosaur remains in Colorado and Wyoming, the first reported from America. Professor O. C. Marsh of Yale College and Professor E. D. Cope of the Philadelphia Academy of Sciences became particularly interested in the dinosaur remains and soon had collecting parties in the field. The main areas from which collections have been made are near Morrison, Colorado, western Colorado, Wyoming, and Utah. The earlier collectors labored under great difficulties, lack of roads, lack of transportation, hostile Indians, and lack of money. The collection of vertebrate fossils requires a great deal of money; invertebrates may be collected without such great expenditure. It was not

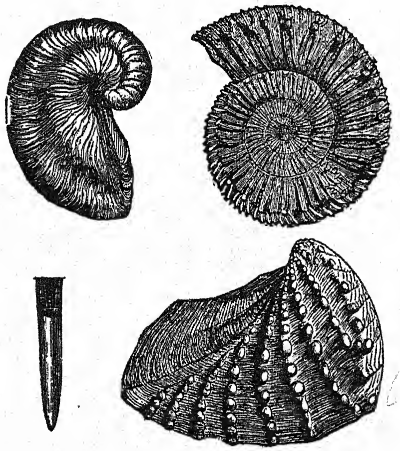

FIG. 399.—Jurassic invertebrate fossils. Upper left, an oyster; lower right, a clam; upper right, a cephalopod showing one suture, the other sutures concealed; lower left, a new type of cephalopod called Belemnite (Jove's thunderbolt). All about one-third natural size.

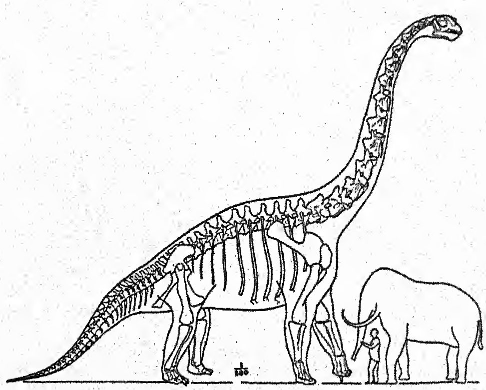

FIG. 400.—The largest species of dinosaur and an elephant. (*After Matthew, permission of the American Museum of Natural History.*)

until early in the twentieth century that the systematic collection of dinosaurs was undertaken. The older collectors picked up bones that lay on the surface and dug out those that could be easily obtained or were not too deeply covered. The modern collector of

dinosaurs finds bones scattered over the surface, finds the place where the bones are in the solid rock by tracing the fragments of bone up-slope to their highest occurrence, and then starts digging and quarrying away the overlying rock. If he finds that the larger part of one animal or several animals are likely to be present, he puts a force of men to remove the rock above the bones. The men may use scrapers and steam shovels to take the materials away and may loosen the solid rock by blasting. As the workers come close to the bone they carefully chisel and cut away the rock from near the bone itself and finally lay bare all of the skeleton present in the rock. The fossils are then removed in blocks of rock as large as can be handled conveniently, and shipped to the museum to be

FIG. 401.—Several feet of rock have been removed from above this dinosaur and the man is preparing the bones so that they can be taken out. (*After Matthew, permission of the American Museum of Natural History.*)

prepared there. The enclosing rock may be cut away to leave the bones in relief, or the bones may be completely freed and mounted as skeletons.

Dinosaur Park.—The best-known dinosaur quarry in the United States is near Vernal, Utah. This was first discovered by a party from the Carnegie Museum. After it had been worked extensively and many skeletons removed, it was finally established as a national park to be known as the Dinosaur Park. A sign along the highway leading east from Vernal directs travelers to Dinosaur Park. Remains of many dinosaurs have been uncovered in the rocks and are exposed there for travelers to examine.

Dinosaurs in Museums.—Some of the best of the dinosaurs from the various quarries have been mounted in the National Museum in Washington, the American Museum in New York City, the Carnegie Museum at Pittsburgh, the Field Museum at Chicago, and the Peabody Museum at Yale University. Each of these museums contains several mounted specimens of different kinds of dinosaurs. Many specimens of dinosaurs from America are in museums in Europe.

The lands must have swarmed with dinosaurs comparable in numbers to the wild animals of present-day Africa, more numerous than the elephants but probably not so numerous as the buffalo once were in North America. Originating in the Triassic, the dinosaur group progressed to greatest size and variety in Morrison time. The Morrison fossils furnish a splendid picture in comparison with which other dinosaur assemblages seem meager. But this picture is one out of many that would be known if conditions had been favorable for preservation of fossils during all of the Mesozoic—one chapter out of a book of a hundred or more chapters; all but two or three of the others are missing. We must then make the most of this fragmentary record.

One collecting from the Morrison or examining the specimens already collected is impressed first by the huge size of some of the specimens. Dinosaur means "terrible reptile" and the name was given more on account of the size of the animals than their ferocity, although some of the species are sufficiently terrible to warrant the appellation. When one finds a single vertebra too large for him to lift or a leg bone 6 feet long and 8 inches in diameter, he is likely to wonder what sort of creatures lived in those days. Some of the dinosaurs of this time were the largest land animals that have ever lived. Specimens more than 70 feet long have been collected, and fragments of considerably larger specimens are known. Some of the largest dinosaurs lived in South Africa at the same time that the Morrison was forming in America; at any rate, larger bones have been found in South Africa than in America. Some animals may have reached a length of 100 feet.

Diplodocus.—The largest type had very long neck and tail, a small head, huge body, and great columnar legs with solid bones. The animal was herbivorous and may have found it difficult, with such a small mouth, to eat food enough to keep alive. But reptiles are not so active as mammals and do not require so much food. These creatures were egg-laying and the eggs were hatched by the heat of the sun. It would seem to have required rather high temperature for several weeks to hatch such an egg, and the presence of dinosaurs in a region would therefore indicate high temperatures and no cold periods. Because of various structures in the animal it seems that it must have lived partially submerged in the water, and that it could not have handled its huge bulk successfully on the land. As it was not a good swimmer, it probably waded about in water deep enough to submerge the body partially and to help support it. This also would account for the fine preservation of many specimens. When animals died they might settle to the bottom and be covered by mud, but fewer than 1 in 10,000 might thus happen to be covered and preserved.

Stegosaurus.—Stegosaurus, though not so large as the one described, was more specialized in some respects. It had huge bony plates on

its back, a specialization for which no reason is apparent. Some of the largest plates are too heavy for one man to lift. Its strange appearance was increased by its very small head, its long, straight hind legs, and very short front legs. Its teeth were well fitted for grinding vegetation. This dinosaur has the distinction of having the smallest brain compared to the size of the animal of any creature that ever existed.

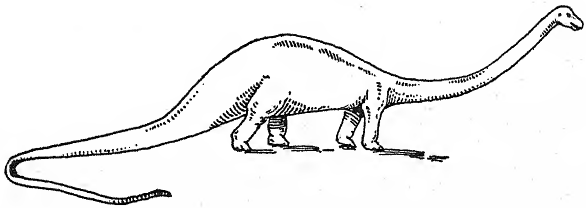

FIG. 402.—Diplodocus, one of the largest of the dinosaurs, about 1/200 natural size, from the Jurassic. (*After Lull.*)

It is the one that led to the erroneous statement that the brain was in the tail rather than in the head. The creature weighed perhaps 30,000 pounds and its brain weighed only about 10 ounces. The brain is so small in comparison to the rest of the animal that it would be possible to drag it backward into the tail region through the space for the spinal cord in the vertebrae. The space in the pelvic vertebra for nervous matter is large enough for three or four such brains. As the greater part of the muscular control required was in the tail region in order to handle the huge tail, pelvis, and hind legs, the reason for such arrangement of nervous tissue is not difficult to see. The stupidity of such a creature can only be wondered at, not realized, and that it could have evolved to that size with such poor equipment for living indicates extremely favorable conditions for such life.

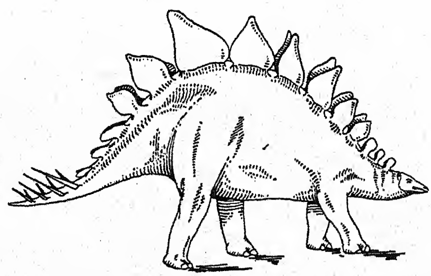

FIG. 403.—Stegosaurus, an armored dinosaur from the Jurassic, about 1/70 natural size. (*After Lull.*)

Carnivorous Dinosaurs.—Another type of dinosaur, a further development of the two-legged Triassic form, had become larger and more voracious. It walked on the hind legs, had very small front legs, a large head, and long heavy tail. Its bones were hollow and it was a large-brained, active creature. It seems to have fed on the herbivorous types of dinosaurs.

Other Dinosaurs.—More than 80 species of dinosaurs are known from the Morrison and the variety in size and kind was very large. The size ranged from those 80 feet long to some not more than 2 or 3 feet long, brain capacity ranged from extremely small to relatively large,

habits ranged from extremes of herbivores to extremes of carnivores. Most of them were egg-laying but it is possible that some were viviparous, *i.e.*, that the young were born alive. Some were light, agile, jumping, possibly almost flying, while others were of the clumsy type which lived mainly in the water. Imagine 80 of the most diverse kinds of mammals that you know from all over the world and the dinosaurs of the Morrison would be as varied as those 80 kinds.

Other Reptiles and Mammals.—Although the dinosaurs dominated, the picture of the life of the upper Jurassic in western North America

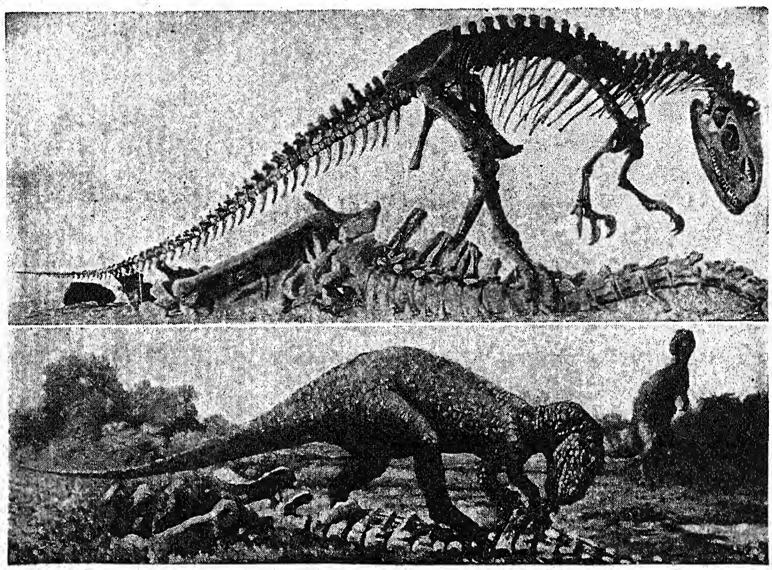

FIG. 404.—Allosaurus, a late Jurassic carnivorous dinosaur of the western United States. The mounted skeleton and restoration represent the reptile feeding on the remains of a large herbivorous dinosaur. (*American Museum of Natural History.*)

would not be complete without some account of the other creatures that were present. A few crocodiles, extremely rare lizards, snakes, and turtles constituted the rest of the reptiles. In spite of the amphibians being so large and important in the Triassic, all of them had disappeared before late Jurassic; at any rate none has been found. Mammals had come to America but they were few in number and very small. Professor Marsh kept two men collecting mammals from the Morrison in an area where they were known to occur, and the result of nearly two years of work by these men was less than a double handful of bones.[1] The mammals were no larger than rats and were extremely primitive, possibly of the egg-laying kind.

[1] Information from Professor Williston, who was associated with Professor Marsh at the time that the collecting was done.

Ichthyosaurs.—In the sea that came down through northern United States from the Arctic Ocean ichthyosaurs were present. These were descendants of the remarkable swimming reptiles of the Triassic. In the field one may find ichthyosaur remains in one bed and dinosaur remains in the beds immediately above. One must have some rather intimate knowledge of these animals to distinguish them from fragmentary remains, although the ichthyosaurs were swimming reptiles with paddles for feet, and the dinosaurs were land-living reptiles. The presence of ichthyosaur remains in a rock identifies it as marine, whereas the presence of dinosaur remains is almost as certain evidence that the rocks are continental, though in a few cases dinosaur fossils have been found in marine strata where the remains had drifted out to sea.

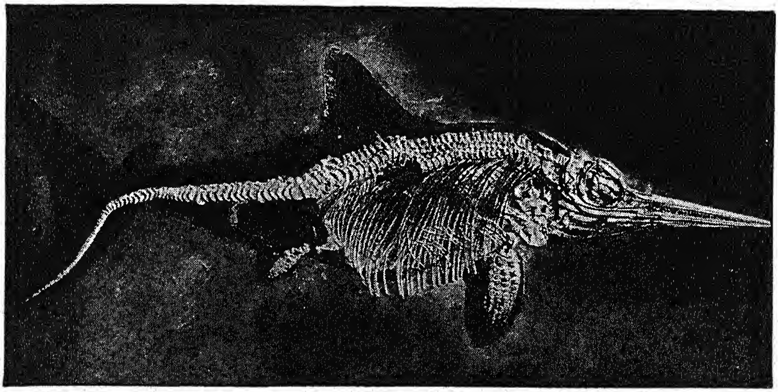

FIG. 405.—A fossil ichthyosaur, showing not only the skeletal structure, but by a carbonaceous residue, the outlines of the body, paddles, and fins. Jurassic slates, Holzmaden, Württemburg, Germany. (*American Museum of Natural History.*)

As with the Triassic, the picture gained from a study of the American fossils is imperfect, and one must go to western Europe in order to complete it. Fossils that supplement those in America are contained mainly in the Solenhofen beds of Bavaria, a marine deposit which contains also some well-preserved nonmarine forms. The Solenhofen beds are limestone of very fine texture which is quarried to be used as lithographic plates; the major part of the fossils come from the quarried blocks. The workmen in the quarries report the finds to paleontologists and thousands of specimens have been collected on the basis of their discoveries. Hundreds of almost perfect ichthyosaur specimens have come from the quarries; ichthyosaurs constitute the most abundant group found in the beds. Every museum of importance in the world contains ichthyosaurs from these quarries. Not more than 10 or 12 ichthyosaur specimens have been found in the Jurassic rocks deposited in the seas that advanced into the Rocky Mountain region from the Arctic region in America, and most of them are exceedingly fragmentary. Comparing this number with

the thousands found in the Solenhofen beds probably does not give a true picture of the abundance of ichthyosaurs in the two seas, as the

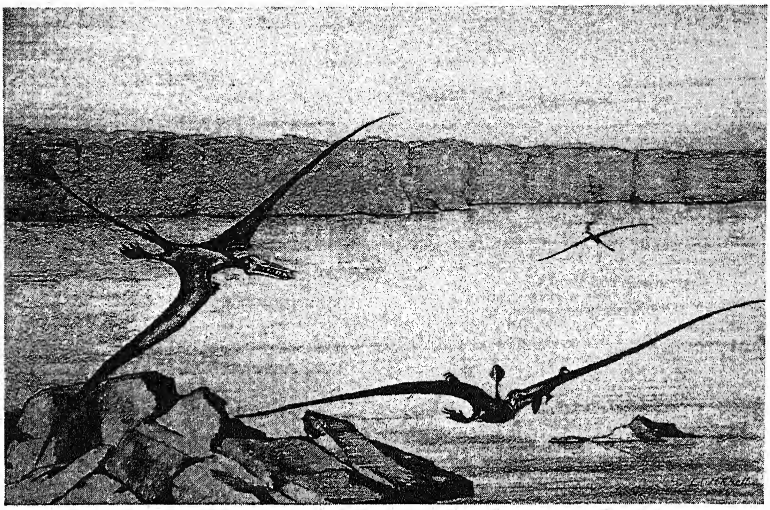

FIG. 406.—Restoration of long-tailed, toothed flying reptile, pterodactyl, from the Jurassic of Europe. (*After M. G. Mehl.*)

Solenhofen beds were perfectly adapted for preserving fossils and the beds in America were not.

Flying Reptiles (Pterodactyls).—Flying reptiles of the Jurassic evolved from the Triassic forms and geologists owe their rather complete knowledge of the flying reptiles of the Jurassic to the remains preserved in the Solenhofen beds. The pterodactyls, as they are called, were probably the most perfect flying vertebrates that ever lived, and their flying apparatus was distinctly different than that of birds or of the mammalian fliers, bats. Their bones were exceedingly light, a bone an inch in diameter having the bony matter not much thicker than an eggshell. The wing developed by the reduction of all but one finger and the great increase in length of that finger (Fig. 410). The other fingers remained as very small vestiges, and some students of the group have thought it likely that the animals hung in trees by the use of these small fingers. The vestigial fingers may be 2 or 3 inches long and the one finger which

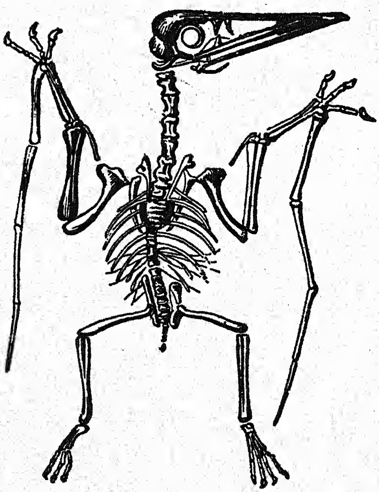

FIG. 407.—Skeleton of a short-tailed, toothless pterodactyl from the Jurassic of Europe.

developed to support the wing membrane, 2 or 3 feet long. It is difficult to understand the mechanism by which such a change came about. The flying itself could not have induced the change as there could be no flight until there was some sort of wing. In order to be preserved in marine deposits, pterodactyls must have flown over the water. Many of them were probably fishers and thus were likely to meet disaster when they tried to catch fish out on the seas. There were too many ichthyosaurs and other voracious reptiles to make diving for fish a safe occupation.

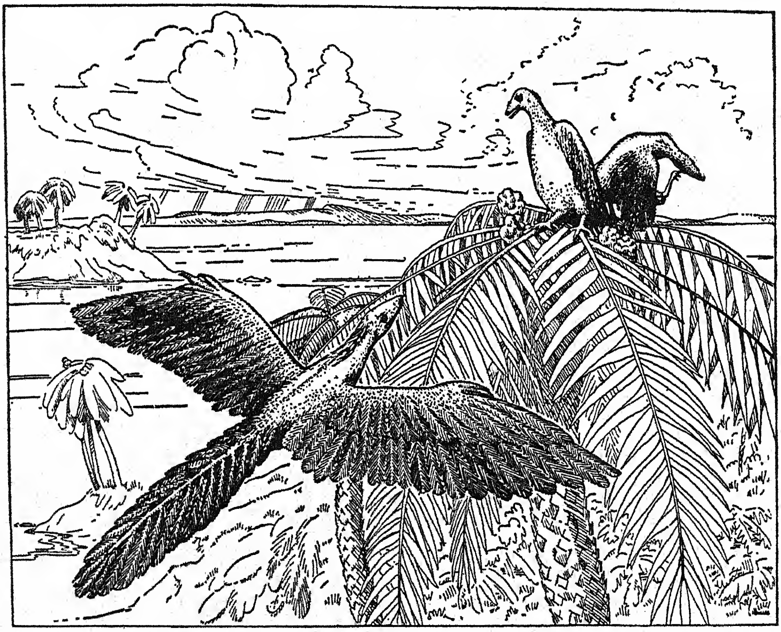

FIG. 408.—The oldest known bird, Archeopteryx, from the Jurassic of Germany. (*From Moore.*)

The Oldest Birds.—We found that during a time of very great reptilian evolution in the Triassic not only did great numbers of kinds of new reptiles appear but much greater changes took place which gave rise to the mammals. During the Jurassic reptilian evolution went on unabated and still another widely divergent group, the birds, was developed. It was in the Solenhofen beds of Bavaria that the oldest bird remains were found, and only three specimens have been found in all the Jurassic of the world. The oldest birds were so much like reptiles that if they had not possessed feathers they would have been called reptiles.

Birds with Teeth and Long Tails.—The first and most striking difference between Jurassic birds and modern birds was the presence of teeth in the Jurassic specimens. The teeth were small and not of great importance but were well developed and functional. Probably the most

impressive primitive character of these birds was the presence of a long, bony tail. Some modern birds are described as having long tails, but the tail is entirely made up of feathers. All modern birds have the tail vertebrae deformed and coalesced into a small misshapen organ. The Jurassic bird's tail was made of twenty-odd vertebrae which were not united.

FIG. 409.—Restoration of the head of Archeopteryx showing the teeth. (*Copied from restoration by Heilmann.*)

Primitive Bird Structures.—The modern bird's wing is highly specialized through the loss of some of the fingers and the union of others. One does not recognize the resemblance of modern birds' wings to the fore foot of an ordinary animal, but the Jurassic bird had all its fingers well developed and the wing membrane stretched between them and attached to the body back of the arm articulation. The modern bird has the vertebrae in the shoulder region firmly united and attached to the breast bone by means of the shoulder girdle to form a rather perfectly

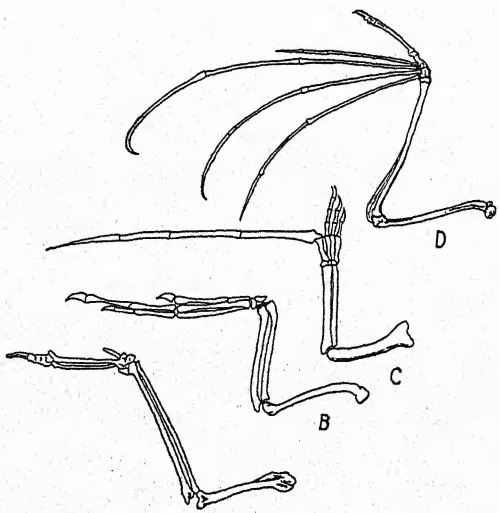

FIG. 410.—(*A*) Modern bird wing, (*B*) Archeopteryx wing, (*C*) pterodactyl wing, (*D*) bat wing.

boxed-in thoracic region. The Jurassic bird had no union of the vertebrae in the shoulder-girdle region and there was no such protection as that possessed by the modern bird. The modern bird has the vertebrae united in the pelvic region and great specialization of the other bones, while the Jurassic bird did not have the vertebrae united and had no

specialization of the other bones of the region. Probably the most fundamental difference between this bird and modern forms was in the vertebrae. The most primitive vertebrae, those of the fishes, were biconcave, *i.e.*, they were deeply hollowed out at each end. Up to Triassic time all vertebrates, whether reptiles, amphibians, or fishes, had biconcave vertebrae. Modern birds have very highly specialized vertebrae with no concavity, but the Jurassic birds had biconcave vertebrae like the reptiles of the Triassic and fishes of all time.

If this creature had not had feathers, it would have been considered as a peculiar lizard with fore legs strangely modified. Such structures as feathers are only rarely fossilized, but those of the bird from the Solenhofen beds are perfectly preserved to minute degree, showing the barblets and scales on the feathers.

Fossil Birds Are Rare.—Birds are among the rarest of fossils and the finding of only a few specimens in the Solenhofen beds does not indicate that they may not have been fairly numerous in their habitat on land. It was only accidentally that they flew out over the sea, as they were not fishers like the pterodactyls.

Comparison of Records of Marine and Land Life.—The record of the sea life of the Jurassic is rather complete in western Europe. If we were to undertake a study of the evolution of the marine forms, we should find fairly steady progress and not marked gaps such as exist in the land life. It is the invertebrate marine life of which the record is fairly complete, but of the ichthyosaurs, plesiosaurs, and many other marine vertebrates the continuity is no better than with the land vertebrates. It is likely that with the extension of geological studies to Asia, Africa, and South America, and with more extensive studies in North America, many of the gaps in the record will be filled.

MISCELLANEOUS

Climate.—Jurassic climate seems to have been warm over most of the earth although there are some differences possibly due to climate between faunas as far north as Alaska and those in the United States. However, the ichthyosaurs, which must have been strictly warm-water animals, came into the interior of north America from the northern seas. Seemingly, they must have lived as far north as Alaska.

Economic Products.—In the United States the Jurassic has only scant deposits of economic value. In California the main gold deposits are partly in Jurassic rocks, and the gold veins were formed in a great series of slates which were intruded by igneous rock. For many years California has been the main gold-producing state in the United States, and much of the gold came either from the Jurassic or from recent deposits derived from the Jurassic. In Alaska there are important coal deposits which may in time become of economic value.

CLOSE OF THE JURASSIC

The northern sea and the Gulf of Mexico sea gradually withdrew during the Upper Jurassic and there were no great differential movements of the land accompanying the withdrawal. The Pacific sea, however, may have been more abruptly pushed off from the land as the first great uplift of the Sierra Nevada Mountains came in the late Jurassic. The uplift was accompanied by intense folding and by the intrusion of some of the greatest lava bodies of the North American continent. One of these stretches more than 800 miles north and south and reaches a width of more than 80 miles in some places. The Jurassic shales of eastern California were intensely folded and metamorphosed, so much so that many of them were changed to slates, and bedding planes and all other ordinary structures of sedimentary rocks were destroyed. In some places the shales were metamorphosed to schists. There is some parallelism between the close of the second period of the Paleozoic, when the mountains of eastern New York and western New England were formed, and the second period of the Mesozoic with the formation of the Sierra Nevada Mountains. A further parallelism between Paleozoic and Mesozoic exists in the Paleozoic marine rocks being mainly in central and eastern North America, the Mesozoic marine rocks mainly Rocky Mountain and western.

CHAPTER XXV

CRETACEOUS OR UPPER MESOZOIC

The Cretaceous derived its name from "creta" (Latin for "chalk") on account of the large amount of chalk present in its rocks. It was named from the chalk cliffs of western France, which stand out prominently along the coast. By many geologists the Cretaceous has been divided into two periods and on consulting some textbooks you may find that the Comanchean or Lower Cretaceous is given the rank of a period.

Sea Oscillations.—As in the Triassic and Jurassic, the seas advanced first from the Pacific Coast but the Sierra Nevada Mountains stood as an impassable barrier and restricted the epicontinental seas to very narrow areas. Almost at the beginning of the period the Gulf of Mexico advanced through Texas, Oklahoma, and Kansas, and northward as far as Wyoming. The Atlantic seas did not advance during the first half of the period. The Cretaceous seems to have been a considerably longer period than either the Jurassic or Triassic, and there were many more oscillations of the land and advances and withdrawals of the sea. These advances finally culminated in a sea which extended from the Gulf of Mexico to the Arctic Ocean and was more than 1,000 miles wide in its widest parts. Its eastern shore extended through eastern Texas, central Oklahoma, central Kansas, thence eastward into Iowa and northward in a northwesterly direction to the Arctic Ocean, and its western shore was not far east of the Sierra Nevada Mountains. In this sea deposits more than 20,000 feet thick were made in some places, although the average thickness of the deposits was not more than 2,000 feet.

Methods of Working Out Ancient Sea Margins.—It may be well to review the ways of determining the extent of ancient seas, using Cretaceous as an example. Figure 412 is a diagrammatic cross section of Cretaceous deposits in Kansas, Colorado, and Utah as they have been worked out by numerous geologists in a long series of years. Figure 411 shows Cretaceous seas. In central Kansas the Cretaceous deposits are thin and patchy, *i.e.*, isolated outcrops occur here and there resting on Permian rocks (Fig. 412).

The patchiness is due to erosion after the deposits were formed rather than to original deposition.

The Kansas Cretaceous rocks contain marine fossils of upper Cretaceous time. The fossils have been determined as lower upper Cretaceous by finding them preserved in a series of rocks where the entire Cretaceous section is exposed. Westward other Cretaceous rocks come in above

those present in central Kansas. Those in the first location are represented by *A* on the diagram and the ones coming in above are represented by *B*. The geologist interprets this condition at the place where *B* begins as the margin of a later Cretaceous (*B*) sea, and if he could trace the margin of the outcrops northward and southward he would be tracing

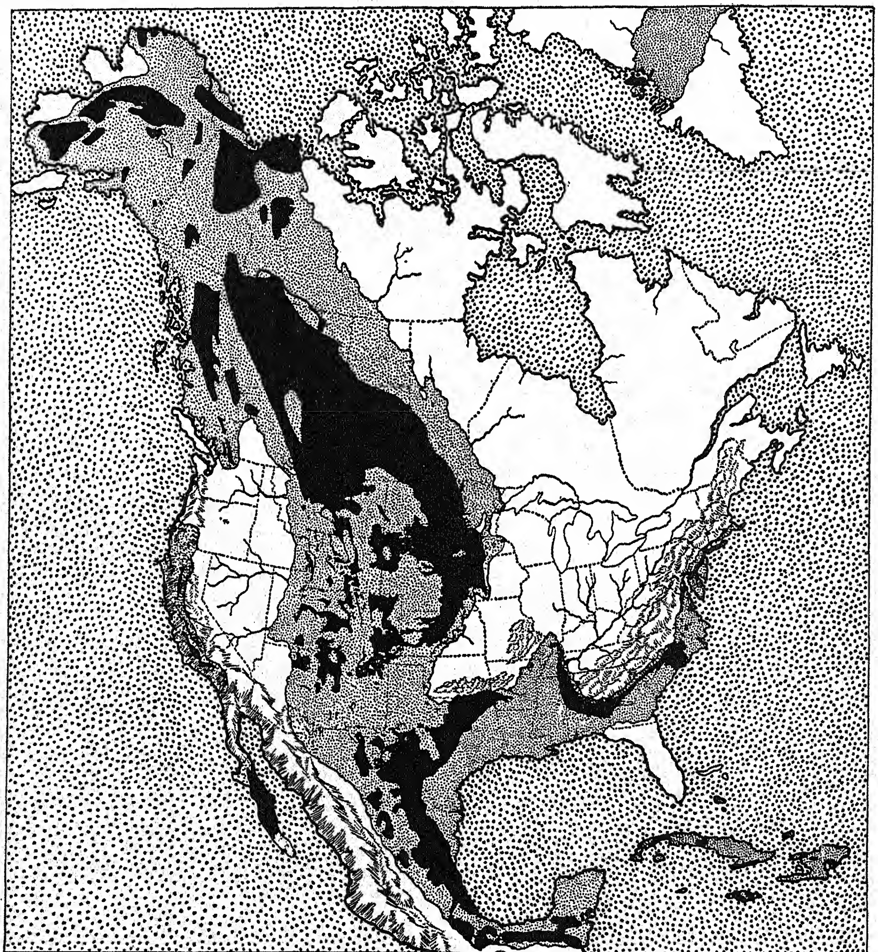

FIG. 411.—Cretaceous seas of about maximum extent. (*Modified from Schuchert.*) Fine stipple represents epicontinental seas. Black represents Cretaceous outcrops.

the old sea beach of that time. There is a considerable amount of uncertainty in such tracing. In the first place, *B* may be covered almost every place by *C* and it is difficult to determine the exact location of the margin of *B*. This margin may be exposed only where streams cut across it and these places may be many miles apart. Take a series of locations along the Pacific Coast as represented in Fig. 411 and draw an outline of

the coast from those locations. Comparing your outline with the actual coast line, you will find that the only place where your diagram is correct is at the crosses but in spite of that you have represented the Pacific Coast in a roughly accurate way, more accurately than the Cretaceous map represents the Cretaceous sea (Fig. 411).

There is one other uncertainty associated with the geologists' determination of the old sea margin. The margin of the rocks that he finds may not represent the actual seashore. The marginal deposits may have been eroded before or after the overlying formation was laid down. Farther westward the margin of *B* is under *C*. *A* rests on the Morrison formation in Colorado and is the oldest of all the Cretaceous that the

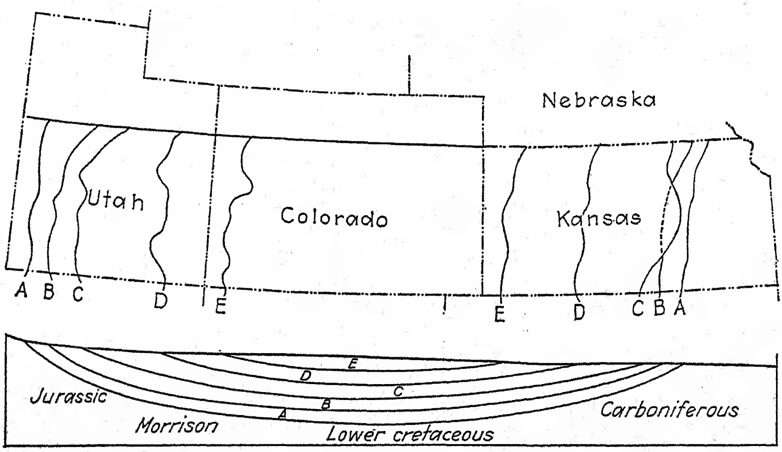

FIG. 412.—A section of the Cretaceous across Kansas, Colorado, and Utah.

geologist is able to find by tracing the rocks over all of the area of deposition.

In Colorado and Utah *E* comes in above *D* and the margin of *E* has been made out by extensive geological study. The westward movement of the margins from *A* to *B*, *B* to *C*, *C* to *D*, and *D* to *E* indicates shrinking of the Cretaceous sea. The western margin of *A* is in Utah, *B* shows small retreat of the sea eastward, *D* and *E* much greater retreats, and the sea in which *E* was deposited was narrow.

In making his investigations the geologist is not able to follow the rock without interruption. If he could trace it along the outcrop and the rock remained the same from one place to another, the history would all work out rather easily, but neither one of these is true. Not only are there great distances between outcrops, but the rocks change in character from place to place. Under such conditions the age of the rock must be determined entirely from the fossil content. The fossils present must be known to the geologist and he must be able to recognize them wherever he finds them. The fossils in each of the members must be distinct

enough to differentiate it from all of the other members. In such a series it is not likely that all of the fossils will be different in each member. Most of them may be the same and the differentiation may be made on the basis of two or three species. Imagine in *A* such an assemblage of fossils as that in life in North America before its discovery by Europeans and in *B* an assemblage such as occurs in America today. Most of the species of the two periods are the same but the leading ones are different. All of the domestic animals were brought in by Europeans and domestic animals dominate at the present time. Several of the species of pre-Columbian time are now extinct or almost extinct. Using the buffalo as an example, in *A* it would have been a dominating form, in *B* it is rarely ever found. Using the horse as an example of the other type, in *A* it is not present while in *B* it is abundant. The geologists, after studying *A* and *B* thoroughly enough to learn these two facts, could determine their identity by these alone.

The geologist may identify formations by tracing them along the outcrops, a good way but with severe limitations because of absence of outcrops. He may identify by the kinds of rock in the formations, which in some cases is very valuable but in many cases useless. As an example, chalk was formed in America in only a relatively limited time and wherever it is found it indicates nearly the same time. Part of *C* of the example used above is chalk and where it is present in Texas, Kansas, and Nebraska it was formed in about the same epoch of time, but had *C* been made of shale, the kind of rock would have been useless in identification, as many of the Cretaceous formations are shale.

Formation of Dakota Sandstone.—We may now return to a consideration of the great Cretaceous sea that cut the North American continent in two from north to south. As this sea advanced northward from the Gulf, it was very shallow near the margin and the waves worked over the weathered material, sorted out the finer particles, and carried them into the deeper waters. Sands were deposited from the beach outward to a water depth of 200 or 300 feet, *i.e.*, as far outward as storm waves could strike the bottom rather vigorously. In many places there were doubtless sand dunes on the shore and the advancing seas encountered little fine material in addition to the sand. But you may raise the objection that the seas would soon advance over a narrow strip of sand dunes and reach the normal mantle rock beyond. The seas were probably advancing at a rate of not more than 1 mile in 1,000 years, and it would not be at all difficult for sand dunes to form along the sea margin in belts 1 mile wide in 1,000 years, so that under some conditions the sea might advance over sand-dune areas for hundreds of miles, the dune areas forming as fast as the sea advanced. However, the rocks would have to be composed of a sufficient amount of sand to furnish sand for the dunes from their weathering. If the rocks were composed of shales

without sand, no sand dunes could form except as the sand blew up from the sea; this would not continue long as the source of sand would be exhausted as the sea advanced over the shale area.

This beach and shallow-water sand formation extends from Texas nearly to the Arctic Ocean. It has been called the Dakota sandstone on account of its development in the Dakotas. Its eastern border is in Iowa, Nebraska, and Kansas, and its western in Nevada, Arizona, and Utah. It is *A* of the example given on the preceding pages and is almost as extensive as the most widespread Cretaceous sea.

Alternation of Marine and Continental Deposits.—The oscillations of the Cretaceous sea brought about some peculiar relationships of the

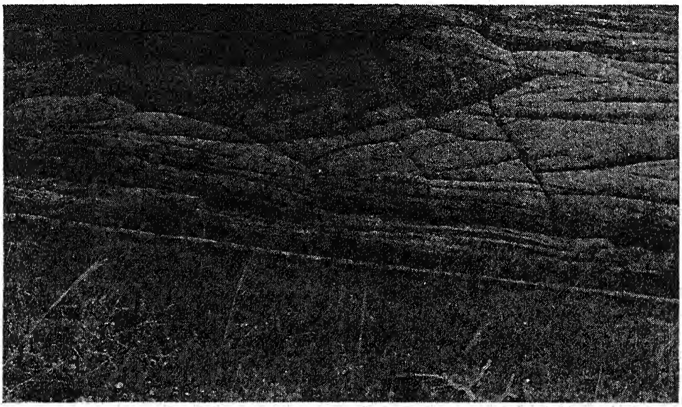

FIG. 413.—Dakota sandstone in Wyoming. Note cross bedding. (*Photograph by E. B. Branson.*)

deposits. In places beds of coal come between formations bearing marine fossils and in some places dinosaur tracks occur in the muds associated with the coal, two evidences of continental deposition. In some places shells of fresh-water animals are associated with the muds and sands above and below the coal; these constitute still another evidence of continental deposition.

Other Cretaceous Deposits.—The most typical of the Cretaceous deposits are in eastern Colorado and western Kansas and Nebraska, where the Dakota sandstone, at the bottom of the series, is followed by several hundred feet of shale, which in turn is overlain by limestone. Interpreting this, we may assume that the margin of the Cretaceous sea had advanced so far northward and westward that no more clays were being deposited in this part of the seas and that the only accumulation on the sea bottom was from shells and bones of sea animals and from chemically precipitated lime. The lowest limestones contain clay which was deposited while the land was near enough for fine sediments to be carried to the lime-forming area. Above these limestones comes the

chalk, which is very extensive in western Kansas and Nebraska, eastern Colorado, and part of Oklahoma and Texas.

Chalk.—Chalk is a limestone of an entirely different type from any thus far studied. It is very soft and in places is made up almost entirely of the remains of one-celled sea animals. The minuteness of these animals and the poor cementation of the deposit make the chalk soft. Where the deposits are free from impurities, the chalk is as soft and free from grit as the crayon used on the blackboard. The crayons used up to about the twentieth century were made from the chalk, but the crayon used now is a manufactured product and is neither limestone nor chalk but is made from burned gypsum. Much chalk is not so largely composed of the small animals as was once supposed and some of it

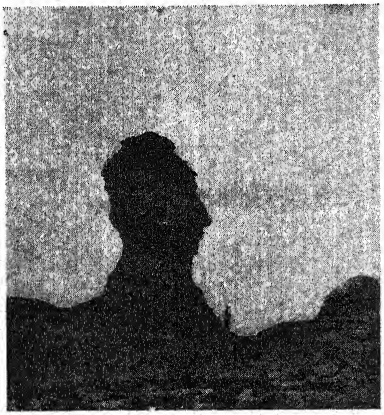

FIG. 414.—An erosion remnant of Cretaceous chalk in western Kansas. (*Photograph by E. B. Branson.*)

FIG. 415.—Foraminifera from the chalk of western Kansas, magnified 20 diameters.

actually has only a small proportion of the minute sea animals. The chalk represents the coming of an important new element into the life of the seas, new kinds of one-celled forms, but the formation of larger bodies of limestone through this element did not last beyond Cretaceous time; chalk is as rare in the post-Cretaceous as in pre-Cretaceous time.

Atlantic Coast Cretaceous.—The early Cretaceous seas did not advance along the Atlantic Coast, but continental deposits of the nature of alluvial fans, flood-plain deposits, and landward sides of deltas formed east of the Appalachians, from New Jersey south to South Carolina, and in the last half of the period seas advanced to the base of the Appalachian Mountains and along the eastern Gulf region as a continuation of the great sea that covered the interior. The deposits along the Atlantic and Gulf Coasts were thin as compared with the deposits of the western interior, a few hundred feet at the thickest. Glauconitic green sands were deposited in many places, but most of the formations are clays and sands.

LIFE OF THE CRETACEOUS

In America the Cretaceous saw the culmination of Mesozoic plants and marine vertebrates and invertebrates. The invertebrate animals

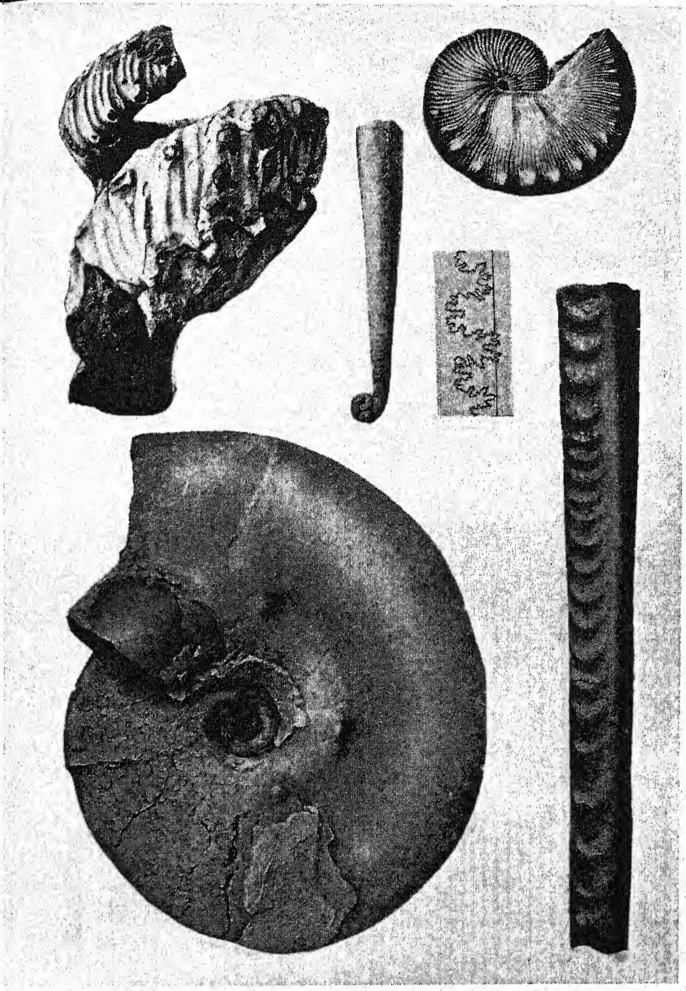

FIG. 416.—Cephalopods from the Cretaceous. (*From U. S. Geol. Survey publications.*) Upper left an incomplete specimen of a form that coils spirally; lower right a specimen with the coiled end missing. The irregular line represents the complex suture of one of the species. All greatly reduced in size.

in Triassic and Jurassic had not been abundant in most places in the American seas, but in the Cretaceous the seas fairly swarmed with great numbers and many kinds. In the main they were kinds with which the student is not familiar, and it will suffice to call attention to a few of the most striking things about them. Clams and cephalopods were the dominant forms.

Cephalopods.—Cephalopods reached their culmination in complexity of partitions and in number of species. This was true for America only and not for Europe. They also reached their maximum size for the Mesozoic. However, they were in old-age stages and showed very decided old-age characteristics. They did not evolve into new forms but the old forms acquired strange ornamentation and shapes. The beginning of coiled cephalopods was in the Ordovician. After that coiled forms dominated, and the last of the straight forms disappeared with early Triassic. Until Upper Cretaceous all of the complex partitioned forms had been coiled, but then they began to uncoil. The oldest part of the shell was coiled and the youngest part straight. Some species almost tied their shells into knots, as shown in Fig. 416. Some became highly ornamented, a quality which accompanies old age or decay.

FIG. 417.—A stone post containing fossil clams, western Kansas. (*Photograph by Walter Keller.*)

Clams.—The clam group was at the height of its development and some of the kinds were large. Shells more than 4 feet across are not uncommon in the chalk of western Kansas. The oyster group, which

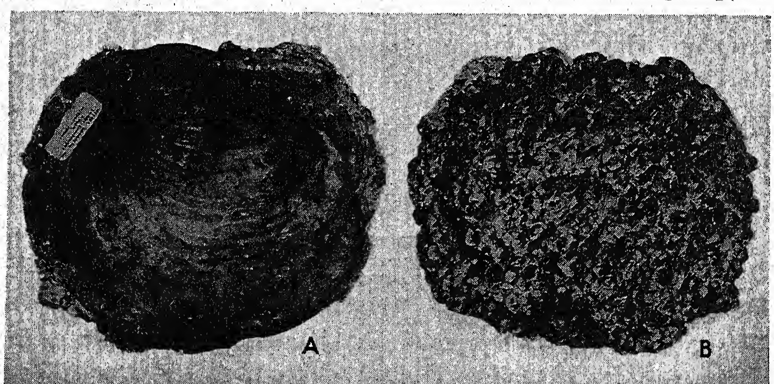

FIG. 418.—(*A*) A large clam from western Kansas; (*B*) opposite side of the same shell completely incrusted with small oysters (about ⅛ natural size).

appeared in the Triassic and increased in the Jurassic, became extremely abundant and of many species in the Cretaceous. Some of them were

several inches long and others were very small. More than 1,000 of the small ones have been found attached to one large clam shell (Fig. 418.)

Mosasaurs.—The seas fairly swarmed with marine reptiles and the numbers of fossils in the marine rocks were supplemented by the land reptiles and by birds that flew out over the sea and became buried in the

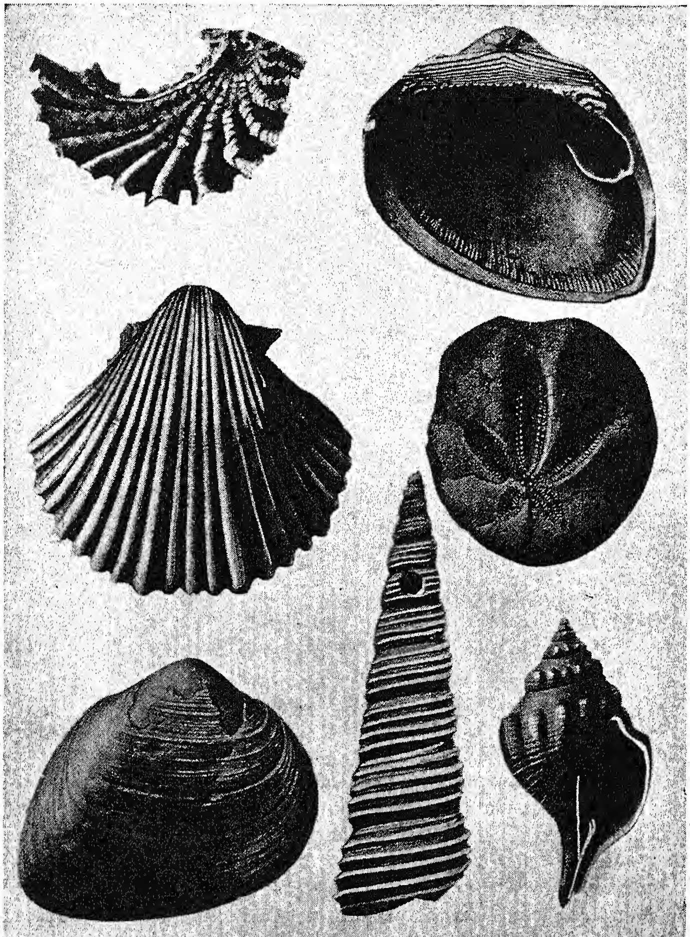

Fig. 419.—Clams and other invertebrates from the Cretaceous. (*From U. S. Geol. Survey reports.*)

marine oozes which finally formed the chalks. One of the great collecting grounds of the world for Upper Cretaceous fossils, particularly the vertebrates, is part of western Kansas. The most abundant kind of animal in the chalk is the mosasaur, a marine lizard with paddles instead of walking feet.

The first specimen collected was found near the town of Meuse in France. It became so well known that a small invading army captured

the town in which it was being exhibited with the purpose of carrying it away. Some monks hid the specimen but the invaders found it and took

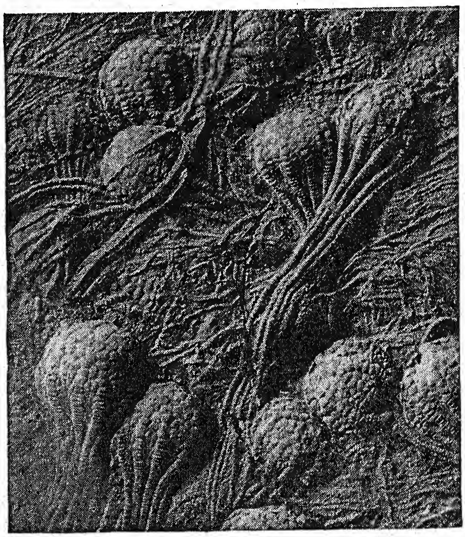

Fig. 420.—A small portion of a slab covered with specimens of the free-swimming Cretaceous crinoid, *Uintacrinus*. From the chalk of western Kansas (¼ natural size). (*After Moore.*)

it away. The figure reproduced on the opposite page is modified from a drawing by Professor S. W. Williston,[1] who did more to make the

[1] It was probably the mosasaurs that made Professor Williston a paleontologist. He lived at Manhattan, Kansas, near the chalk beds, and went with his professor of geology of the State Agricultural College to get fossils from the chalks. The finding of numerous bones in the chalk aroused his interest to such an extent that he went to Yale College to study vertebrate fossils under Professor Marsh, then the best-known student of Cretaceous vertebrates in the United States. At the time when Professor Williston first went to the chalk beds, bones were scattered widely over the surface where the chalk had weathered, but since then hundreds of collectors have worked over the exposures of chalk and have taken way all of the larger bones exposed on the surface. It is only as the chalk weathers and is eroded further that other specimens appear. It gives a collector a decided thrill to find a clean, perfect fossil bone lying on the surface of the chalk and then to locate other bones that are sticking out of the chalk. He may then take a pick or a knife, dig away the chalk and find more clean, hard bone. The collector never knows how much of a specimen he will find after he has located some part of an animal in the solid rock. The bone he is working on may be the last one present in the series, or the series may be complete from tip of snout to end of tail. After the animal died it may have been torn to pieces by other voracious animals, and only under rare circumstances did a complete animal settle to the bottom and get covered with mud to fossilize in its entirety. Even if the entire animal were preserved in the chalk the chance for some person to find it at the stage when none had been eroded away would be small. The chances are thousands to one that streams, while cutting valleys in the chalk, would have carried away or destroyed part of the bones of the entire specimen. Thousands of specimens of mosasaurs have been collected from the Kansas chalks, and although good specimens are rare nearly every important museum has at least one.

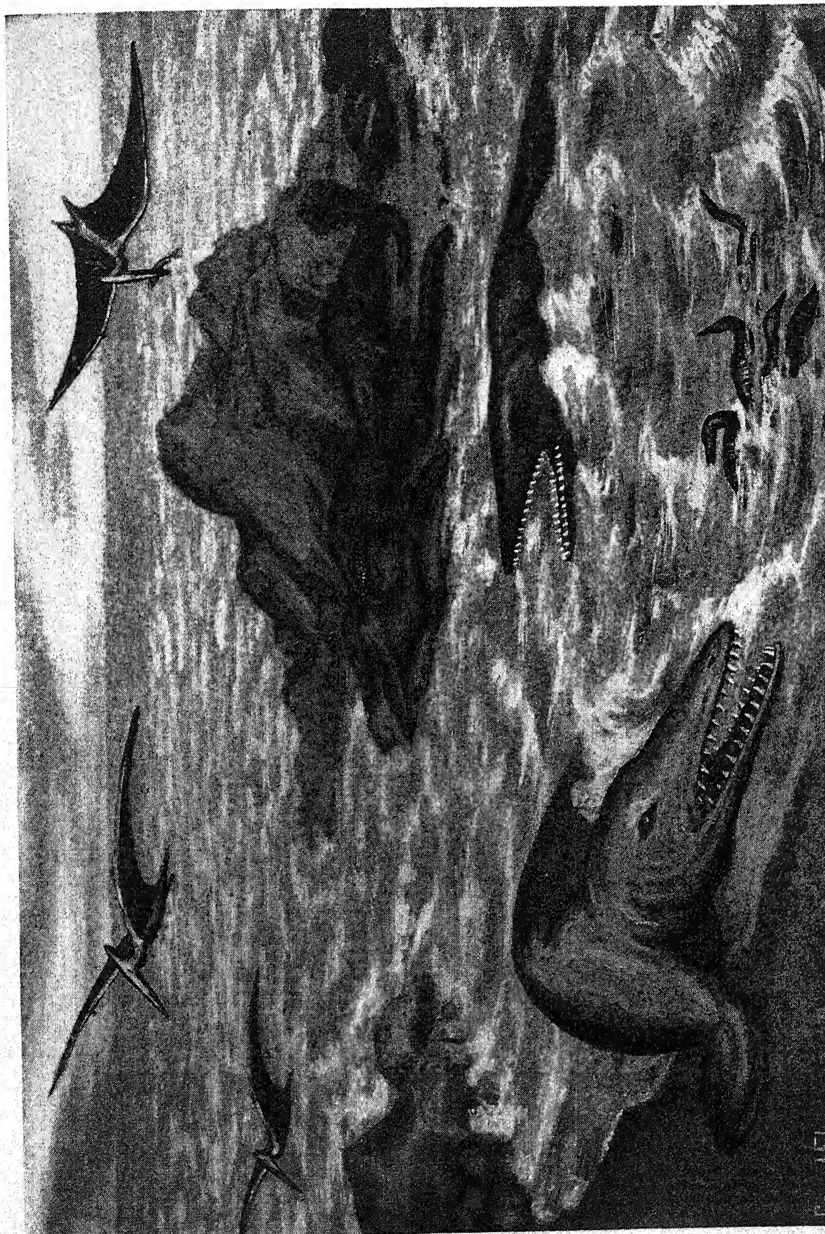

FIG. 421.—A western Kansas group of Cretaceous animals. Pterodactyls flying, turtles at the extreme right, mosasaurs eating a plesiosaur on the rocks in the center, two mosasaurs in the water, swimming birds in the right foreground.

mosasaurs of North America known than any other investigator. Some of the mosasaurs probably reached a length of 60 feet and were comparable in length to small whales although they were more slender.

Flying Reptiles.—Associated with the mosasaurs in the chalk were fossils of the final forms of the flying reptiles. Greater specialization had created here a most perfect flying machine and the largest of the flying animals that ever existed. The largest specimens had a spread of the wing of 26 or 27 feet, but the whole framework of the animal weighed only a few pounds. Specialization was nearly all in the wings and head; the latter became greatly elongated and had a strong backward-projecting crest which served as an attachment for the wing muscles. The beaks came to acute points and the animals may have been able to spear their prey. As their remains have been found only in marine deposits they probably caught mainly sea animals. The earlier pterodactyls had long, strong teeth, but those of the chalk had evolved to a toothless stage. Pterodactyls[1] must have lived on the shores of all the seas of North America and they probably flew widely over the lands, but their remains have been found only in the chalks of western Kansas, and one bone in Washington. It seems remarkable that their bones are unknown from any other of the widespread Cretaceous deposits of North America.

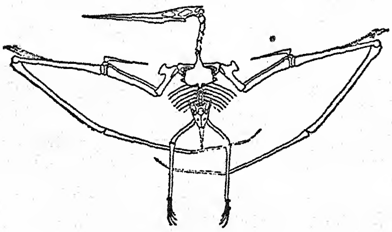

FIG. 422.—Skeleton of a pterodactyl from the Cretaceous of western Kansas. (*After Williston.*)

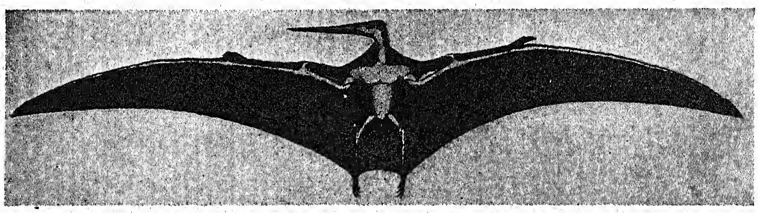

FIG. 423.—Pterodactyl from the Cretaceous. (*Restored by Herrick E. Wilson.*)

[1] In collecting from the chalks of western Kansas one should not expect to find pterodactyl bones every day or even every week. One experienced collector found three specimens in three months. One of these consisted of a part of one wing, another of part of a head and one wing, and another of fragments of wing bones and body bones. The finding of the rarer thing in the chalks is a matter of chance as well as perseverance. One collector had one day to spend in the chalk, and although he found nothing else worthwhile he took out a very fine small pterodactyl, one of the most complete that has ever been collected. Another experienced collector, with one day to spend in the chalk beds, found and took out possibly the most perfect wing that has ever been found. The same collector might work for a year without finding anything else comparable to it.

Turtles.—In the chapter on the Triassic the first appearance of turtles was mentioned. In the chalks three or four kinds of marine turtles are present. Some of these reached a length of 8 or 9 feet, and their skulls were as large as the skull of a horse. Their feet were paddles, but not so perfect paddles as those of the mosasaurs. Their backs were not covered with bone as are most turtles of the present.

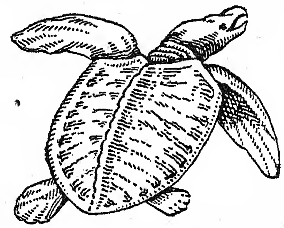

FIG. 424.—A turtle from western Kansas. (*After Williston.*)

Plesiosaurs.—At least one other marine reptile, the plesiosaur, was present in the seas in which the chalks were deposited. The extremely long, slender necks of the plesiosaurs have led to a rough description of them as animals with bodies like that of a turtle and neck and head like those of a snake (Fig. 425). Some of the animals became as large as the large mosasaurs. Plesiosaur remains are as rare as those of pterodactyls.

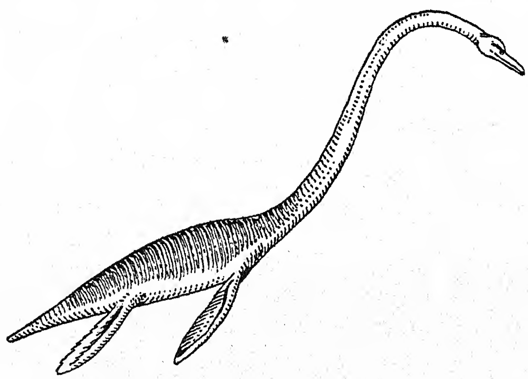

FIG. 425.—Plesiosaur from western Kansas. (*After Williston.*)

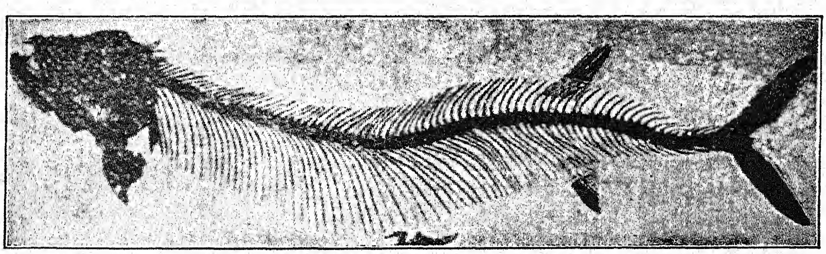

FIG. 426.—Skeleton of the large marine fish; Portheus of late Cretaceous age. (*Preserved in the University of Kansas Museum.*) Some specimens of this fish are 15 feet long. (*After Moore.*)

Fishes.—In spite of the abundance of reptile remains in this chalk the collector finds fully three times as many fossil fishes as all reptiles

combined. In taking out the skeleton of one mosasaur he may destroy the skeletons of several fishes. This was the first time of great abundance of the bony fishes. Most of the kinds in the Age of Fishes were of the more primitive nonbony types. Some of these fishes were no mean antagonists of the reptiles. One species was 18 to 20 feet long and had its jaws armed with long, sharp teeth. Even the smaller species were well provided with teeth. Although the bony fishes dominated, some of the sharks of the Cretaceous were much larger, and at least one species attained the size of the large mosasaurs.

Birds.—The collector of chalk fossils is never satisfied until he has found a fossil bird, and these are the rarest of all the fossils.[1] Men have worked for years in the chalks without finding a single bird bone. Although all of the birds from the chalk had teeth some of them were rather highly specialized in other respects. Some still had the biconcave fish type of vertebrae but others had developed the highly specialized type of vertebrae of modern birds. One form had lost its wings and had developed webfeet. It was as truly water-living as the marine reptiles (Fig. 428). Some of the other birds had as highly specialized flight organs as modern forms (Fig. 434). One difference that is constant between all Mesozoic birds and those of post-Mesozoic is the presence of teeth in the former and the lack of teeth in the latter. The preservation of a bird seems always to depend upon some especially favorable type of sedimentation. No birds are known from the Mesozoic of Europe except from the Solenhofen Jurassic beds, and none is known in America except from the Cretaceous chalks.

Dinosaurs.—In the northern Rocky Mountain region continental deposits developed over wide areas in the uppermost Cretaceous and

[1] The first bird known from the chalk had a rather remarkable history. It was collected by Professor Mudge of the Kansas State Agricultural College, who did not recognize it as a bird. He boxed it up and directed it to Professor Cope of the Philadelphia Museum. However, before he could send it a friend of his appeared who asked him to send it to Professor Marsh of Yale College. Accordingly the direction on the box was changed and the specimen was sent to Professor Marsh, who later wrote a large book on birds of the chalk beds. On receiving the specimen Professor Marsh wrote a paper describing it, and as an extra paragraph said that associated with the other bones of the bird were some little reptile jaws of a new type. The paper hadn't been out long when Professor Marsh published a short correction saying that the so-called reptile jaws actually belonged to the bird and that birds with teeth had been found. He was ridiculed in scientific papers as well as in newspapers as the man who had found birds with teeth. However, other specimens were discovered soon after and all of them from the chalk had teeth.

Professor Marsh turned the tables on other geologists in a dramatic way. The bird from the Jurassic of the Solenhofen beds had been known for a long time, but no teeth had been described from its jaws. On going to the museum at Berlin Professor Marsh asked for the privilege of examining the specimen and, using a sharp needle in preparing it, he was not greatly surprised to uncover teeth in the jaws, which had been overlooked by the former students.

here for the last time we get a picture of the dinosaurs and their associates. The first American picture of this group was in the upper Triassic of the Connecticut Valley, the second in the upper Jurassic of the Rocky

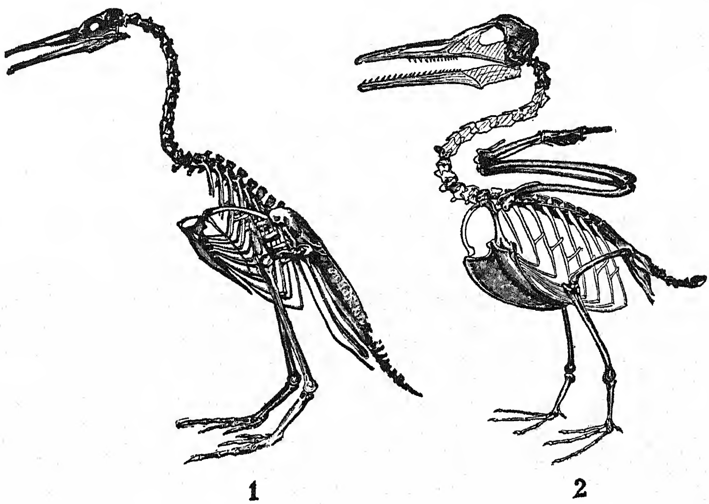

FIG. 427.—Skeletons of upper Cretaceous toothed birds. 1. *Hesperornis*, 1/16 life size. 2. *Ichthyornis*, 1/4 life size. (*After Marsh.*)

Mountain region, and the third and last in the uppermost Cretaceous of the Rocky Mountain region. The largest of the dinosaurs had disappeared and peculiar specializations had taken the place of mere bulk,

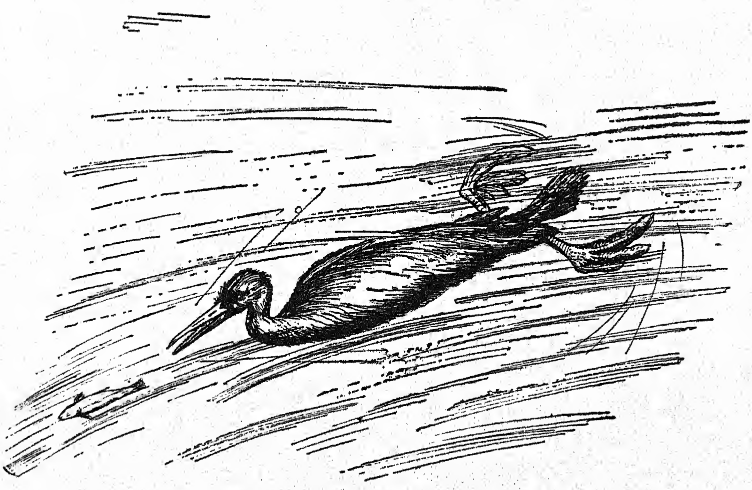

FIG. 428.—Restoration of *Hesperornis*, the Cretaceous swimming bird. (*After Gleeson.*)

although they were still by far the largest animals that lived on the land. One form had developed a very large head (in some specimens 9 feet long by 5 feet broad) with two or three horns on it. Its body was

relatively low, broad, and heavy. It was named Triceratops on account of the three horns of the first one discovered. One of the Jurassic dinosaurs had the distinction of having the smallest brain for the size of

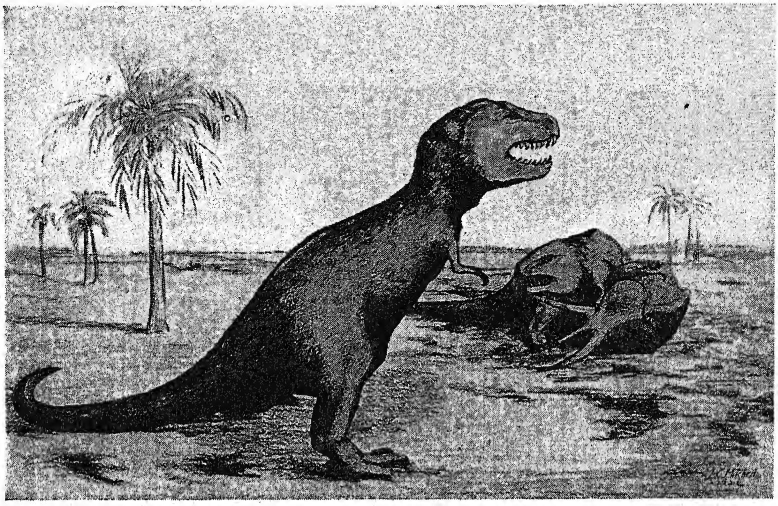

FIG. 429.—*Tyrannosaurus*, the largest of the carnivorous dinosaurs. One animal feeding on a Triceratops, another Cretaceous dinosaur. (*From M. G. Mehl.*)

the animal of all creatures, but Triceratops had the smallest brain compared to the size of the head of any known animal. A recent expedition of the American Museum to Mongolia discovered what seem to be ancestors of the Triceratops type. It found dozens of skulls of shape and character of the Triceratops, ranging in size from about 1 foot long up to

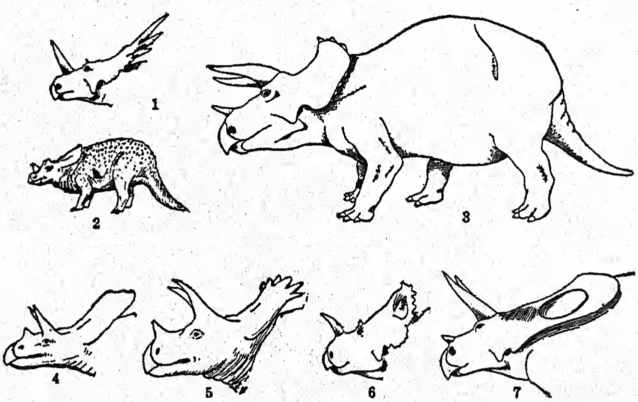

FIG. 430.—Several species of the horned dinosaurs, Ceratopsidae. The best-known genus, Triceratops, is shown in 3. (*After Berry.*)

almost the size of the American Triceratops. Although Triceratops has been known for 50 years the two years of collecting in Mongolia produced more specimens than have come from all of North America.

A carnivorous dinosaur that walked on its hind feet and had very short, almost useless front legs was the last of its type and reached the culmination of its kind in size and voracity. It was named *Tyrannosaurus rex*, "king of the tyrant reptiles." As it stood on its hind legs it was some 25 feet high. Its head was more than twice the size of a horse's head, and its teeth were long, sharp, and strong.

Another peculiar species was the duck-billed dinosaur. It, too, walked on its hind legs and had very weak front legs. The front of its head was flattened and widened so that it looked very much like the bill of a huge duck. It had flat teeth, adapted only for feeding on plants.

FIG. 431.—A piece of Dakota (upper Cretaceous) sandstone containing two leaves.

These descriptions may seem to be altogether of the peculiar types of dinosaurs, but they were the dominant ones. The race was rapidly moving toward extinction, and the latest dinosaurs known in America were present here. There is some disagreement as to whether the top of this dinosaur-bearing formation should be called Cenozoic or Mesozoic, and on the interpretation of some geologists dinosaurs persisted into the Cenozoic, but according to the majority they disappeared near the close of the Mesozoic.

CRETACEOUS PLANTS

An event of far-reaching significance was the appearance in the early Cretaceous of the Atlantic Coast region of flowering plants. Plants of various types had been abundant since the Middle Paleozoic, but flower-

ing plants were very rare until the Lower Cretaceous. They evolved rapidly and soon spread westward from the Atlantic Coast to the westernmost Cretaceous deposits. In the interior of the Rocky Mountain region they were preserved first in the Dakota sandstone (Fig. 431) of the Upper Cretaceous, where they are exceedingly abundant. Probably no other formation is better known for its plants than the Dakota sandstone. Maple, cottonwood, oak, walnut, sassafras, willow, and many other kinds of present-day types were common, but none of the modern species had appeared. One result of the appearance of flowering plants was that the insects that evolved the process of honey making from blossoms could come into existence and that animals of various kinds could become specialized in their diet to eating that type of plant only.

MILD CLIMATE OF THE CRETACEOUS

Large reptiles and subtropical plants have been found in Cretaceous rocks in high latitudes, indicating mild temperatures over all the world. There is no evidence of extreme aridity any place during the period, but aridity is a condition dependent upon local conditions and likely to be present in every period. It is only where it is extreme and widespread that evidences of it are likely to appear in the rocks.

ECONOMIC PRODUCTS

The economic value of Cretaceous mineral products is greater than all the rest of the Mesozoic and equal to that of some periods of the Paleozoic. The great coal deposits of the Rocky Mountain region and eastward from the Rockies are mainly Cretaceous. Coal here is comparable in amount to that of the late Paleozoic in the eastern part of the United States, although the quality is by no means so high. Most of it is low-grade bituminous or lignite. As coal occurs at many levels conditions at several times during the Cretaceous must have consisted of widespread swamps over large areas in which vegetation of great luxuriance grew. Vegetation here was mainly flowering plants rather than the other types which formed the coal of the late Paleozoic. The coal reserve in the Cretaceous rocks is more than two hundred billion tons, and is being mined only very sparingly. Next to coal, petroleum is the most important Cretaceous product. The oil fields of parts of Texas, Wyoming, Montana, Colorado, New Mexico, Utah, and Mexico are Cretaceous in age. Texas and Wyoming are the only states that are important producers from the Cretaceous, and the total production is smaller than that from the late Paleozoic rocks and the still later Cenozoic rocks of California.

CLOSE OF THE CRETACEOUS

In the late Cretaceous nearly all of the ranges of the Rocky Mountains were uplifted and folded, so that western North America from being an

area of deposition became high with great numbers of mountain ranges. Mountain making was in progress from Alaska to Cape Horn and was even more intense in South America than in North America. Uplift was general over North America and the Appalachian Mountains had another period of growth. Since their origin in late Paleozoic they had undergone almost constant erosion and were nearly peneplaned before the uplift at the close of the Cretaceous.

CHAPTER XXVI

THE CENOZOIC ERA[1]

The term Cenozoic means recent life and it was applied to the latest geologic era because some species of animals that are still living have representatives in the oldest of the Cenozoic rocks. The uppermost Mesozoic rocks contain no modern species; the lowest Cenozoic rocks which rest directly on top of them contain some modern species. As

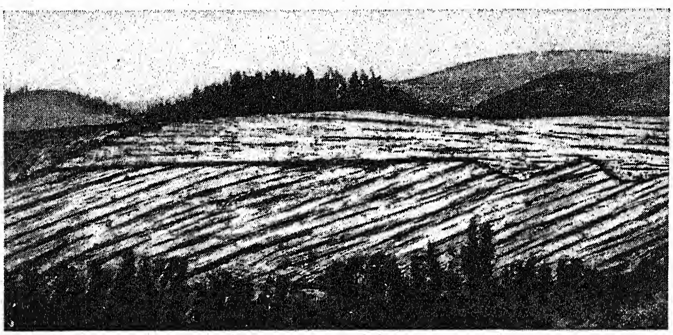

FIG. 432.—A retouched photograph of early Cenozoic rocks on tilted Mesozoic rocks. (*Photograph by E. B. Branson.*)

species, distinct as the modern ones, could not have originated from the older ones without some transitional forms, it seems certain that considerable time elapsed between the laying down of the uppermost Mesozoic and the lowermost Cenozoic from which fossils have been collected.

Divisions of the Cenozoic.—Although the Cenozoic lasted no longer than some of the periods of the Paleozoic and Mesozoic, it has been divided into five periods, as listed below, on the basis of the proportion of modern species of mollusks present in the fauna.

Pleistocene, most recent, 90 to 100 per cent of living Mollusca.
Pliocene, more recent, 50 to 90 per cent of living Mollusca.
Miocene, less recent, 20 to 50 per cent of living Mollusca.
Oligocene, little of the recent, 10 to 20 per cent of living Mollusca.
Eocene, dawn of the recent, 1 to 10 per cent of living Mollusca.

Obviously this division into periods does not follow the principles outlined on page 317 for period differentiation, but at the time that the

[1] The earliest investigations of the Cenozoic were made near Paris in the Paris Basin, but most of the names were given by Sir Charles Lyell, an eminent English geologist.

names were proposed no principles for geologic divisions had been formulated. Most geologists do not recognize the Cenozoic divisions as of period rank and it seems logical to refer all Cenozoic and Recent to one period. That is, we are living in the first period of the Cenozoic era and no extensive sea invasion of the land in which marine strata could form has occurred.

Early Cenozoic Land.—The truncated folds covered with horizontal Eocene beds in the Appalachian, Cordilleran, and western mountains, indicate something of the amount of erosion that must have taken place before the Cenozoic seas could overlap the Mesozoic and older rocks as they must have done to produce the relationships between Cenozoic and Mesozoic rocks shown in Fig. 432. The early overlap was not on the areas that had been formed into mountains in the closing stages of the Cretaceous but rather on the low-lying areas. If the seas were to start to encroach on the North American continent at the present time, on account of the general rise of sea level they would first overlap the lowlands at the mouths of the Mississippi and other rivers and it would be a long time before they would reach far enough inland to rest directly on consolidated rock of previous periods. The land is probably not so emergent now as it was when Cenozoic history began and the mountains have been eroded to a much greater degree.

Eastern Cenozoic Seas.—The Atlantic and Gulf coastal areas have been somewhat unstable during Cenozoic time. During each of the epochs seas encroached over narrow areas near the existing coast lines and withdrew after relatively short periods. The oscillations were much smaller and less numerous than those that occurred during the Cretaceous period. Mexico and Central America were more largely inundated than the rest of North America.

The seas were shallow and the sediments were nearly all of near-shore types, alternating sands and clays. Each epoch is represented by a few feet to about 500 feet of sediments and slight unconformities separate the rocks of each epoch. In the Gulf region the deposits are thickest and the delta of the Mississippi started as the Eocene sea invaded to southeastern Missouri. In parts of the Gulf region the seas may have remained without withdrawing at the close of epochs, but the Gulf region sediments show numbers of alternations of subaqueous and subaerial conditions as one would expect in a delta. Coal formed in some of the delta swamps and even along the Atlantic coast nonmarine formations alternated with marine.

Although Central America was under the sea several times during the Cenozoic and several thousand feet of sediments were deposited, it seems to have formed a land bridge between North and South America in the middle part of the era and in later time.

Pacific Cenozoic Seas.—The Pacific sea invasions were no larger than the Atlantic but sediments accumulated to a much greater thickness. More than 25,000 feet of strata were deposited, but no single section is that thick. The sediments are coarse, volcanic ash makes up no incon-

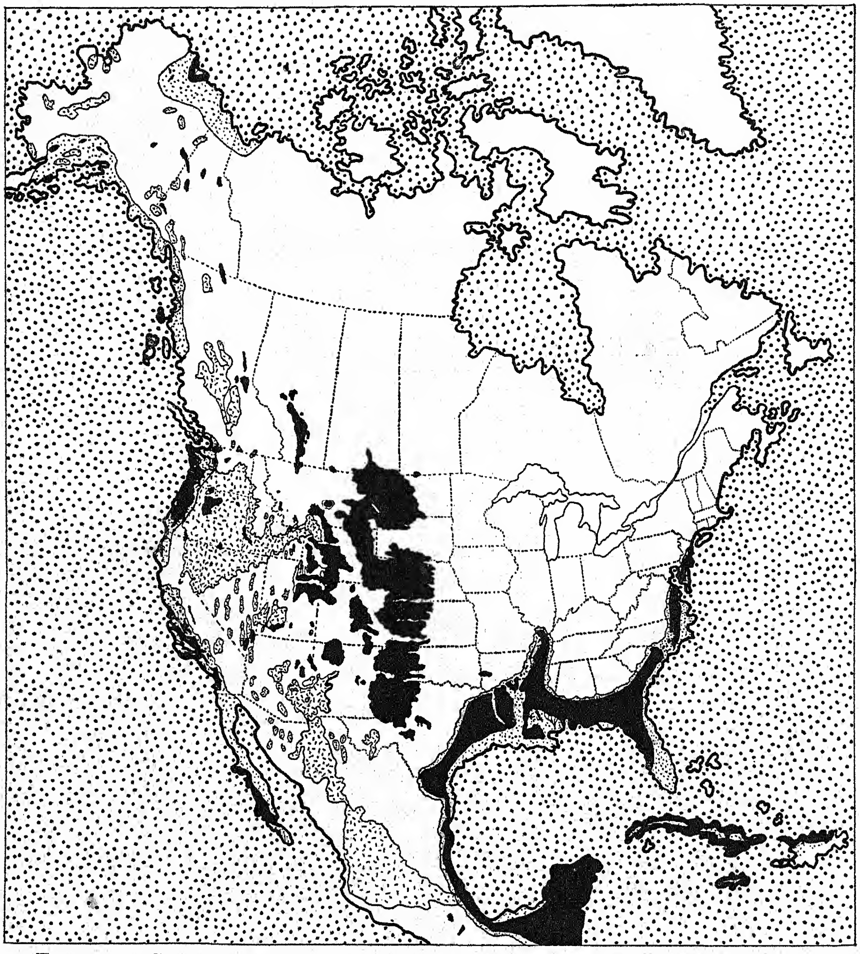

FIG. 433.—Cenozoic seas and outcrop. Fine stipple represents epicontinental seas. Black represents outcrops of Cenozoic sedimentary rocks. Dashes represent outcrops of Cenozoic igneous rocks.

siderable part of the formations, and lava flows alternate with sediments in many places.

In the Puget Sound region a great delta formed and more than 100 coal beds are interbedded with the other sediments. In California diatoms (one-celled plants) make up formations more than 1,000 feet in thickness. Here accumulated a diatomaceous ooze which as a usual thing forms only in deep water and far from shore.

Continental Deposits.—To most geologists the greatest interest in the Cenozoic strata of North America centers about the continental deposits of the Rocky Mountain region and westward. The main reason for this interest is the preservation in those deposits of fossils which give a key to the development of many types of animals.

As the upper Mesozoic seas withdrew from the Rocky Mountain region they were partially filled with deltas built by extended consequent streams which crossed the newly emergent land. This land was irregular in topography but the irregularities were not pronounced. They were something like those of the surface of the delta of the Mississippi at the present time. In the depressions rank vegetation flourished and much of this finally became coal. Alluvial fans from the higher lands formed over the tops of the deltas and merged with the topset beds of deltas to form widespread nonmarine deposits, the oldest of which were the youngest of the continental Cretaceous rocks. The later deposits of the same kind, formed after the seas had withdrawn from the continent, were the oldest of the Cenozoic deposits. These deposits were most extensive in Montana, Wyoming, and North and South Dakota, and the amount of coal in them is very large.

Contact between Mesozoic and Cenozoic Rocks.—You will readily see that the contact between the Mesozoic and Cenozoic rocks could not be sharp under such conditions and that geologists would find difficulty in determining just where to draw the boundary between the eras. The change from one type of sediment to another would not be significant. When we contrast this contact with the line of demarcation between eras as we have considered them before, this seems the wrong place to draw the line, but such relationships must have developed in some places between the latest deposits of every era and the earliest of the succeeding era. The Mesozoic-Cenozoic relationship is better preserved over larger areas than the others because there has been much less chance for its destruction by erosion. The contact between Cenozoic and older rocks when the Cenozoic seas advanced over the eroded lands is one of unconformity (Fig. 432).

Cenozoic Volcanism.—Part of the Cenozoic experienced a great amount of volcanism. In Washington, Oregon, Utah, and Idaho, lava ranging in thickness up to 5,000 feet flowed out over an area of more than 200,000 square miles. The surface of the Columbia plateau is made up of basalts formed at this time. Near the Pacific Coast in both North and South America great numbers of volcanic mountains formed. In Arizona, New Mexico, Colorado, and Utah many dikes, necks, sills, and larger intrusive masses of Cenozoic age have been exposed by erosion, and many areas are covered with lava flows, mainly basalt. The volcanic action in Yellowstone Park is of late Pleistocene time.

Cenozoic Mountain Making.—The mountains of western North America and South America had various degrees of uplift during the

Cenozoic and many of them owe most of their elevation to Cenozoic movements. The Pliocene and Pleistocene epochs witnessed direct elevation without folding of most of the Rocky Mountain ranges and Coast ranges. The Appalachian Mountains experienced several up-warpings during Cenozoic time, and most of their height above sea level is due to Cenozoic uplifts. All of the folding preceded Cenozoic.

Basins between the Mountains.—Although the Rocky Mountain ranges formed at the close of the Mesozoic they were not uplifted to their present heights. Between the various mountain ranges there were low basins and in these basins the continental deposits formed. The deposits are extremely irregular. Where streams have cut through them and laid them bare so that they may be observed, one sees thick beds of sandstone gradually grading to shales along the beds. Sandstones and shales alternate from top to bottom so that one formation may have many beds of sandstone and many beds of shale. The materials of the sandstones and shales are not well sorted because rivers do not sort materials thoroughly except in their large deltas where they spread over wide areas. If one visualizes the sort of deposit formed on a wide flood-plain, where the stream working laterally builds up one side and cuts down the other, cuts off meanders, abandons oxbows, probably fills the oxbows with fine muds at times of flood, cuts across old oxbows and fills the crosscuts with sand, gets gravels from the bluffs and alternates them with sands and clays in some places, he has some idea of the complexity of the river deposits of the Cenozoic.

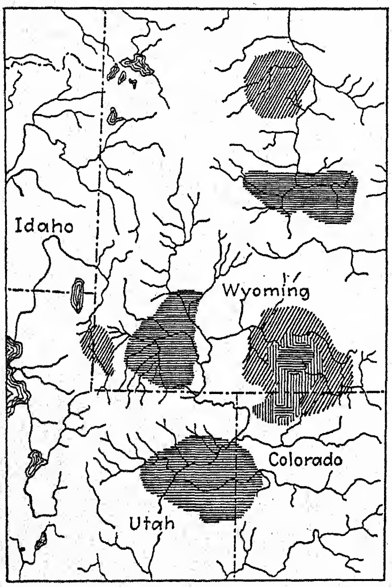

FIG. 434.—Areas of Eocene continental deposits in the Rocky Mountain region. (*Data from U. S. Geol. Survey.*)

The sites of deposition did not remain in the same places throughout all of the Cenozoic era. In southern Colorado and northern New Mexico a considerable area was covered by deposits during the first part of the era, but this site ceased to receive sediments during the last three epochs. Several basins might be receiving sediments at the same time, but be entirely disconnected.

LIFE OF THE CENOZOIC

During the closing stages of the Mesozoic the typical reptiles, birds, and mammals were dying off or undergoing great changes, and with the

earliest Cenozoic the animals contrasted strikingly with those of late Mesozoic. Whereas Mesozoic is known as the Age of Reptiles, Cenozoic is known as the Age of Mammals. None of the large and highly specialized reptiles of the Mesozoic remained; the dinosaurs, flying reptiles, and many kinds of swimming reptiles had disappeared.

In place of the reptiles, mammals, which had been present, small in size and few in numbers, during the Mesozoic, became the dominant type of land life. In the oldest of the Eocene continental deposits remains of primitive[1] generalized mammals, all small, have been found but they are rare.

Early Eocene Life of One Region.—Try to imagine a landscape such as may be found at the present time in southern California, hemmed in by low mountains, vegetation luxurious and of subtropical types, palm trees common, the animal life consisting mainly of generalized types of mammals, most of them small. If you could have caught one and examined it you would have found it unlike anything that you had ever seen or read of. It might have resembled a small horse, or might have looked more like a dog. You might really have been examining an ancestral horse. In the oldest Cenozoic deposits horses were no bigger than small dogs, had four toes, walked flat-footed, and only remotely resembled modern horses. Another of these animals looked something like a cat and more like a dog, but it was neither. It did not have sharp shearing teeth or well-developed canine teeth and it did not have claws. It was a primitive type of carnivore or flesh eater, one of the ancestors of the carnivores of the present time. Among the trees you would have missed the variety of birds that are present almost every place in modern

[1] By primitive types it is meant that the forms were like those from which you would expect the more specialized species to develop. By generalized we mean that the animal contains characters that become distributed in the higher forms. One of the higher forms will have some of the characters of the generalized type and lack others, so that in a large number of species of the higher types one would find all of the characters possessed by the generalized types.

For instance, all of these mammals had four or five toes, whereas with the progress of evolution many of them lost one or more of the toes. Man is primitive in respect to the number of toes. All of these mammals had forty-four teeth, but during the progress of evolution most animals lost some of their teeth. Man has thirty-two teeth and is somewhat specialized in that respect. Some mammals have become very highly specialized in respect to teeth, having lost all of them. Specialization does not necessarily mean advantageous progress. It may even mean degeneration.

The early Cenozoic mammals were all flat-footed, *i.e.*, none of them walked on the ends of their toes as many mammals do at the present time. All of them had generalized teeth; they were not specialized either for grass eating, flesh eating, insect eating, or fruit eating. Nearly all mammals of the present have some such specialization of teeth. Hogs' teeth are not specilized for any particular kind of diet and so may be said to be generalized or primitive.

None of those primitive mammals had developed the burrowing habit of the rodents or the swimming specializations of many modern mammals.

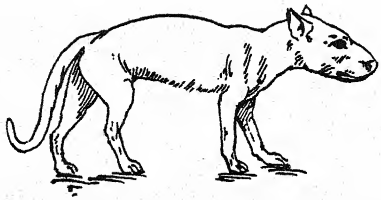

FIG. 435.—An ancestral carnivore of the Eocene. (*After Scott.*)

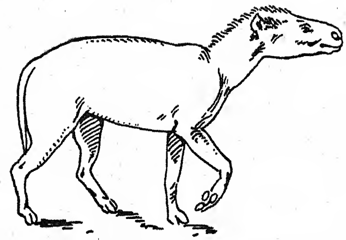

FIG. 436.—An ancestral four-toed horse from the Eocene. (*After Scott.*)

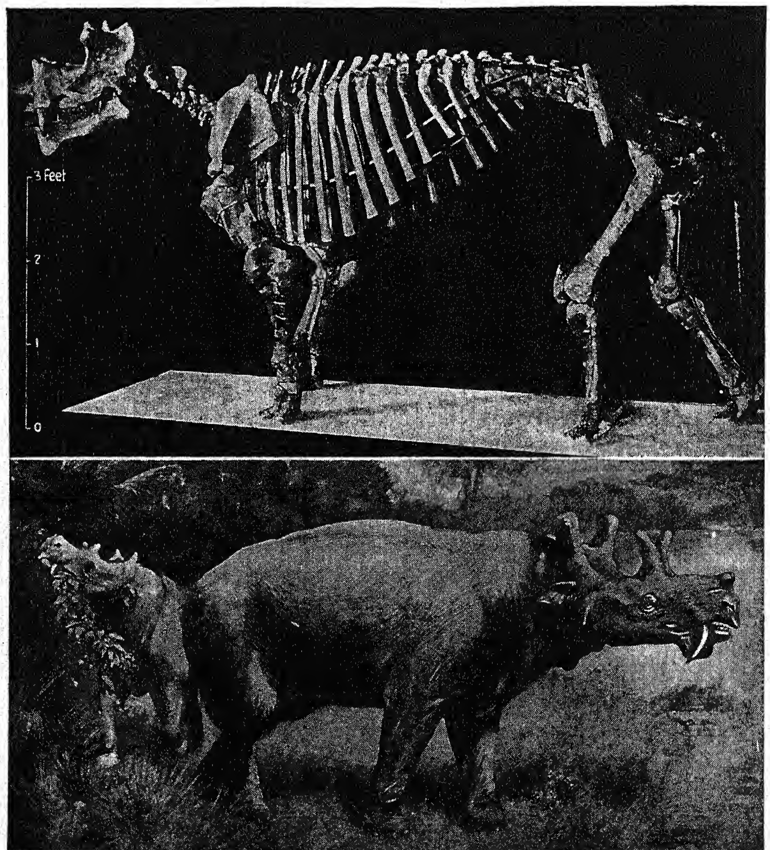

FIG. 437.—Skeleton and restoration of the giant among Eocene mammals, about 5 feet high. (*American Museum of Natural History.*)

time. Birds were present but of few kinds and probably in very small numbers. However, birds fossilize with great difficulty and are always rare as fossils no matter how abundant they were, so that we may be incorrect in considering that the number of birds was small.

You would have seen few reptiles although it may be that modern types of reptiles played a more important part than we suppose. Turtles, crocodiles, lizards, and snakes were present but not in great numbers or of many kinds. Their remains have not been found associated with the oldest Cenozoic mammals of America, although they have been found in other parts of the world.

Rapid Changes in Animals.—Conditions for rapid changes of mammalian species were favorable. Many types of highly specialized mammals appeared, great numbers developed, large forms developed from small ones, and all of the main types of mammalian life were present by the end of the Eocene. Several kinds of mammals reached elephantine size during the Cenozoic. Before the close of the first epoch one kind had attained a height of 5 feet. Its head was large and many-horned, and upper canine teeth of the males were large and curved. As its remains were found first near the Uinta Mountains, it was named Uintatherium. One of its striking peculiarities was that it had the smallest brain for the size of its body of any known mammal.[1] Most mammals are large-brained, and the proportion of brain to size of body is always larger than in other types of animals. The large mammals of the early Cenozoic were herbivorous.

Horses.—Probably the history of the horse group is better known than that of any other. We have already considered the horse that occurred in the oldest Cenozoic formation, an animal no larger than a small dog, four-toed, walking flat-footed, having forty-four teeth not differentiated or highly specialized, hoofs not well developed. In the next higher formation of the Eocene many changes took place. The animals became larger, about the size of Shetland ponies, and the number of toes was reduced to three on each foot.[2]

[1] Recall that one of the Mesozoic animals had the smallest brain compared to size of body among all animals (page 399), and that another had the smallest brain compared to the size of its head (page 422).

[2] The reduction of toes seems to have come about by the animal starting to walk on the ends of the toes. You may illustrate this with your own hand by placing it flat on the table with the forearm erect. Now start to raise the hand so as to rest it on the ends of the fingers rather than on the flat of the hand. As the hand comes up, the thumb ceases to connect with the table. Keep on raising the hand until the little finger also ceases to connect with the table. You now have the condition of the three-toed horse, with the middle toe bearing the greater weight and the side toes resting on the ground and helping bear the weight. He has really become an odd-toed creature, the middle toe being of the greatest importance. As the thumb or first toe ceased to touch the ground it gradually atrophied or ceased to develop, and as we observed, in the oldest horse it was already missing, assuming that this four-toed form

The loss of the toes, accompanied by changes such that the animal walked more on the ends of the toes, forced other changes in the animal's foot. The change from flat-footedness to walking on the ends of the toes caused changes in muscles and in relationship of the feet to the legs. A striking change was in the elongation of the carpal bones, the bones between the fingers and the wrist as you illustrate them with your hand. These bones assumed an erect position and increased in length greatly out of proportion to the increase in size of the animal.

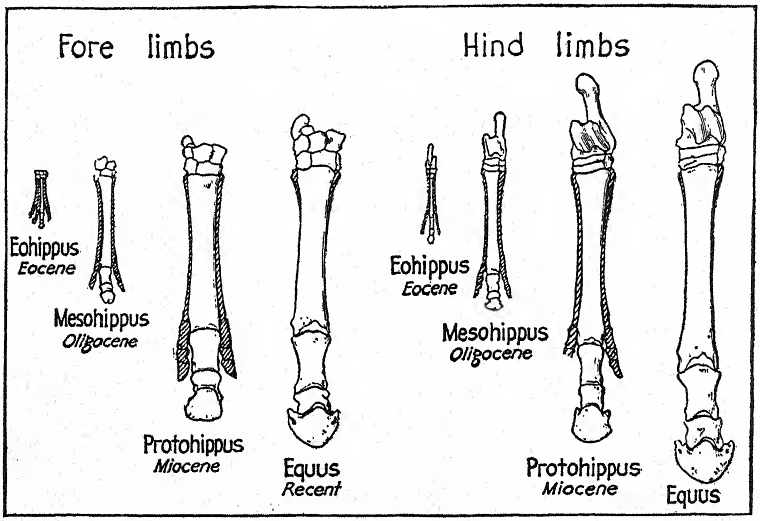

FIG. 438.—The lower part of the limbs of modern and fossil horses, drawn to scale, showing progressive enlargement of the central digit and the gradual disappearance of the side toes. The part of the limbs represented is that below the wrist or ankle. (*After Moore, modified from Scott.*)

Only one of the five carpal bones remains in the one-toed stage and it has increased greatly in length and size. From a bone 2 inches long in the earliest horse it became 18 inches long in some of the larger horses. The foot lengthened to some 20 or 22 inches and had a single line of bones extending from the wrist[1] to the hoof.

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had developed from an original five-toed animal. During the upper Eocene the same thing happened to the fifth toe, the little finger as represented by your hand; every vestige of that toe had disappeared before the end of Eocene time.

Continue to raise your hand into a still more erect position so that the arm and hand are in a straight line from the elbow to the tips of the fingers. The fingers on either side of the middle drag backward as your hand is raised and finally cease to touch the table. This seems to have happened to the horse as it began to walk on the middle toe, and by glacial time it had lost all but the middle toe. The other two, however, remained as mere splints or vestiges and are present in the modern horse.

[1] People unfamiliar with the anatomy of horses are likely to call the wrist the knee. The part of the horse about the height of the knee of man, which seems to function like the knee of man, is really the wrist, and the knee is up against the body.

All parts of the horse were changing all of the time, but some parts more rapidly than others. The lengthening of the foot required decided changes in other parts of the body. The horse was becoming a grazing animal, eating grass from the ground. With an increase in the length of the foot that brought its head 18 inches higher than in the early stages, an adjustment was necessary unless it was to get down on its knees or lie down in order to feed. The horse's head and neck both elongated at

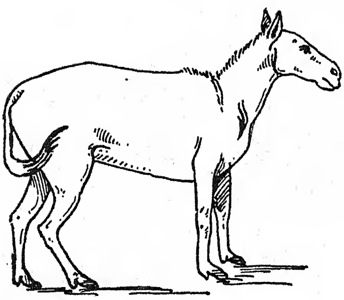


FIG. 439.—Oligocene horse, about the size of a large sheep, with three toes on each foot. (*After Scott.*)

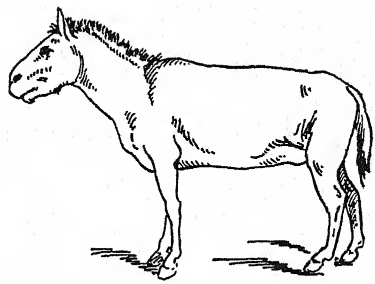


FIG. 440.—Pleistocene horse, about the size of a small modern horse. (*After Scott.*)

the same time as the foot increased in length, so that there never was a time that it could not readily reach the ground with its mouth.[1]

In the early stages the horse could not be a grazer because grass had not developed. First it had to eat shrubs and branches of trees. As the grasses developed, the horse formed the habit of eating them. Its teeth, however, were not well fitted for grass eating. They were small and too

(*a*) (*b*) (*c*) (*d*) (*e*)

FIG. 441.—Evolution of horses' teeth, from Eocene to recent. (*After Osborn.*) (*a*, *b*) From the Eocene, (*c*) from the Oligocene, (*d*) from the Miocene, (*e*) from Pleistocene to recent.

much alike in hardness throughout each tooth to make them effective grinders of grass. The later evolution of the teeth was as striking as that of the feet. They became large and elongated, but most essential of all, developed very complex patterns of enamel alternating with a softer material called dentine (Fig. 441). We found from studying the

[1] Such discussion of changes does not imply that geologists know what caused the changes, which came first, which was the more important in the evolution, or anything further than that the changes actually took place. Biologists working with modern forms are in most cases unable to tell what causes changes. Investigators of modern forms are unable to work out causes for changes in forms in which they can observe the changes taking place, and geologists are absolutely helpless in working out causes of changes in forms that lived so long ago.

rocks that hard layers stood out while soft layers wore down, and that where alternating layers of hard and soft rocks were exposed the topography consisted of ridges and valleys. The tooth of the horse, by having harder and softer layers on edge, remains rough as long as such layers exist. By increasing the length of the originally short teeth the animal's length of life could thus be increased greatly, for the wear caused by eating grasses reduces teeth rapidly. Probably the Pleistocene horse lived several times as long as the early Cenozoic horse, although such a conclusion is not susceptible of proof.

Many species of horses developed during the changes from early Cenozoic to Pleistocene. More than 60 species have been described from

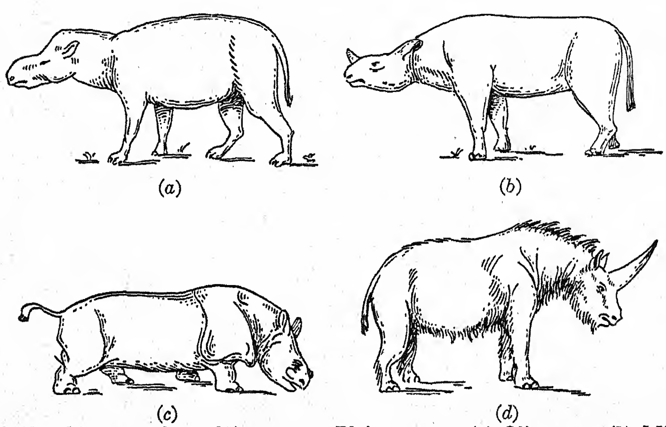


FIG. 442.—The rhinoceros from Oligocene to Pleistocene. (*a*) Oligocene, (*b*) Miocene, (*c*) Pliocene, (*d*) Pleistocene. (*After Osborn.*)

North America alone and it is probable that as many more will be found. Seven or eight species lived at the same time and horses may have been as abundant as the buffalo once were on the great plains. However, horses entirely disappeared from both North and South America long before the coming of Europeans to the continents.

Horses are known as odd-toed ungulates (odd-toed hoofed animals) for the reason that the usual number of toes was three or one. A four-toed horse was mentioned but it was a temporary stage between five-toed and three-toed. Many other odd-toed ungulates appeared during the Cenozoic.

Rhinoceros.—After the horse the most abundant odd-toed ungulate in North America was the rhinoceros, along with which the tapir and the horse are the only odd-toed ungulates extant. The rhinoceros lived in great numbers in North America and its bones make up real bone beds of late Cenozoic age in parts of Nebraska and Kansas. Several kinds existed, but three main types roamed North America at the same time. One of these was a large heavy-limbed form like the modern African

species, which lived in low timbered regions. Another was a light-limbed, slender, grass-eating type, and a third was intermediate between the two in size and habits.

Tapir.—The tapir is a three-toed form with modern representatives only in Africa and the American tropics. In Central and South America it is the largest of the wild animals, but the evolution of the feet has not gone beyond the clumsy three-toed type (four on the front) and none of the fine adjustments of elongated carpal bones has come about in its evolution.

Even-toed Ungulates.—The general consideration of the odd-toed ungulates leads up to the study of the much more important even-toed ungulates, which are represented by hundreds of species and by the most important of the modern animals with the exception of the horse. Cattle, sheep, deer, antelope, camels, and goats are some of the even-toed ungulates. Instead of having one, three, or five toes they have two or four toes.[1] They seem to have branched off from the odd-toes ungulates very early in Cenozoic time. Several species of camels developed in North America during early Cenozoic and they seem to have flourished up to about the time of the glacial period.

Carnivores.—The carnivorous groups of mammals appeared in large numbers and many species, culminating in size in the huge saber-toothed tiger, which was very abundant in the late Cenozoic just before the glacial period. Not only was this cat very large but the great development of its upper canine teeth distinguished it readily from all of the other large cats (Fig. 444). A remarkable occurrence of the remains of the saber-toothed tiger is at Rancho la Brea near Los Angeles, Cali-

[1] If you will again use your hand to illustrate the foot of the primitive lower Cenozoic flat-footed mammal you can see the process through which the even-toed ungulates went as they changed to two-toed. As before, have the forearm erect, the hand flat on the table. Raise the heel of the hand slightly until the thumb is off the table and the weight of the arm and hand rests on four fingers. The thumb now is useless; gradually it atrophied or ceased to develop in the even-toed ungulates and the animal came to walk on four toes. Continue to raise the hand to a more erect position, but instead of bringing the weight to bear on the middle finger bring it to bear on the two middle fingers.

The outer two fingers now become useless; gradually in the even-toed ungulates they ceased to develop and two-toed forms such as cattle, goats, and sheep resulted. The splints of the outer toes remain as vestiges of the former structures in almost all forms. Many of the earlier species of the even-toed ungulates had four functional toes and several of the living forms have four toes, although the outer two are not functional. The evolution of the rest of the foot paralleled that of the odd-toed ungulates. Two palm bones functioned in the same way as one in the horse, and the ankle of the animal is in the same position as that of the horse. The head and neck of the large species lengthened at the same time that the foot elongated. They, too, became grazing animals and their teeth became modified in much the same way as those of the horse. Specialization in teeth went even farther than in the horse, as some of the even-toed ungulates lost all of the teeth from the front part of one jaw.

fornia, where large seepages of oil occurred and the volatile parts of the oil evaporated, leaving an asphalt lake. Animals seem to have come to the lake to drink and to have mired in the asphalt. Thousands of specimens of the saber-toothed tiger have been taken from these lakes. Their flesh was not preserved in the asphalt but their bones did not decay after death.

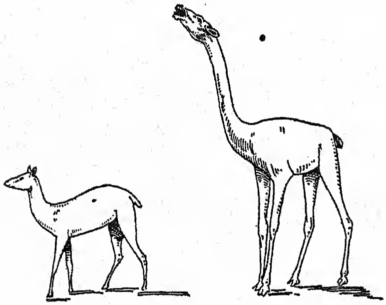


FIG. 443.—Oligocene camel on the left, Miocene-Pliocene camel on the right. (*After Berry.*)

Primates (Apes and Man).—Man and the apes form the family called Primates, and in the oldest Cenozoic formations fragmentary remains of apes have been found. The lower Cenozoic primates were very primitive and generalized, small apes were scarcely distinguishable from some other primitive types of mammals. In North America apes were never numerous, and none of them was highly developed. The rise of the higher types of primates came mainly in Africa and Asia.

Elephants.—Eurasia was favorable for mammalian evolution in the Cenozoic. Odd-toed ungulates, even-toed ungulates, carnivores, and many other forms were much like those of North America. The elephant group, however, was entirely distinct and was well developed and large before it migrated to North America. It seems to have originated in Africa and the first elephant-like species were small and resembled

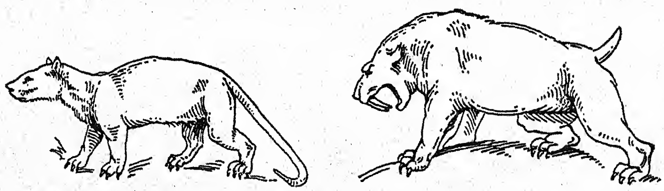
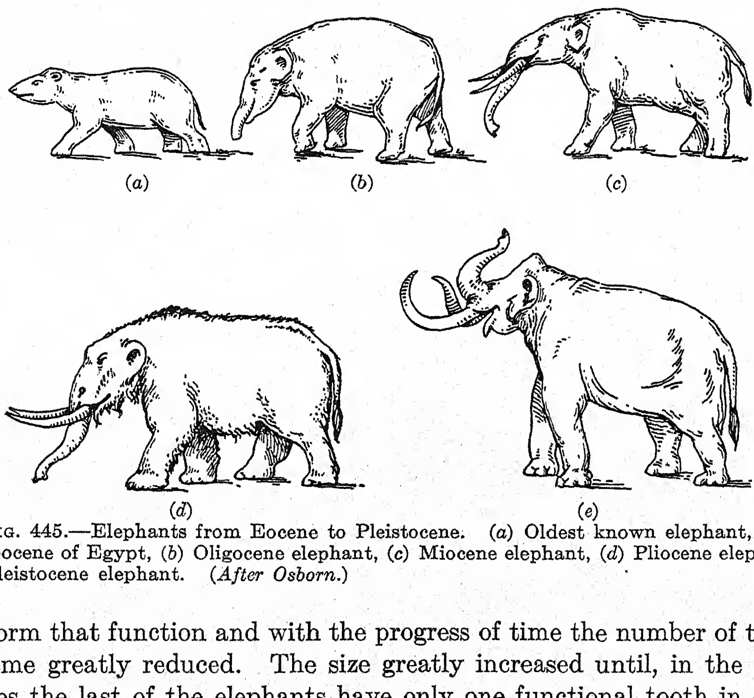


FIG. 444.—Eocene cat on the left; Pleistocene cat, the sabertooth, on the right. (*After Scott.*)

modern hogs. This was only a superficial resemblance, one of shape rather than of structure. The oldest elephants came from early Cenozoic rocks. They had protuberant snouts but no trunk and no tusks. With the progress of Cenozoic time they increased greatly in size and the snout elongated and became prehensile. Unlike the horse the elephant did not reach the ground by an elongation of the neck and head. They remained short but the elongation of the trunk allowed the animal to drink from the low-lying pools and to browse from the tops of trees.

The outer incisor teeth increased in length in both upper and lower jaws and finally developed into tusks. In some species only the upper

incisors enlarged, in others only the lower, in still others both upper and lower, while the females of many of the species lost the incisors and were tuskless. There was no development of the feet parallel to that of the horse; they remained large and clumsy. The earliest known elephants had somewhat specialized teeth, but the tendency was for teeth to become very large and to have alternating vertical layers of enamel and dentine, such as are present in the horse. As the mouth and head did not keep pace with the rest of the body in size, it was necessary that the mouth be a very effective food gatherer in order to provide the animal with the food that it needed. The small teeth of the early forms could not



(a) (b) (c)

(d) (e)

Fig. 445.—Elephants from Eocene to Pleistocene. (*a*) Oldest known elephant, from the Eocene of Egypt, (*b*) Oligocene elephant, (*c*) Miocene elephant, (*d*) Pliocene elephant, (*e*) Pleistocene elephant. (*After Osborn.*)

perform that function and with the progress of time the number of teeth became greatly reduced. The size greatly increased until, in the final stages the last of the elephants have only one functional tooth in each jaw, not counting the tusks. A peculiarity of the teeth is that another one comes in behind the one that is functioning and gradually pushes it up and out so that elephants shed their teeth several times during life. The pain caused by the incoming tooth is known to animal keepers as elephant toothache; it sometimes drives the animals nearly frantic.

About middle Cenozoic time, before the North American animals migrated into South America, elephants migrated across some land bridge between Asia and North America and finally went across the isthmus into South America. They spread all over North America, and the remains of the two main types, mastodon and mammoth, have been collected from every state in the United States.

Domestic Animals.—It is remarkable that all of the domestic animals were brought into the Americas by Europeans, save only the small camels of South America. Horses, camels, dogs, cats, hogs, all were early denizens of North America, but none survived until man arrived. All originated from old-world species.

South American Mammals.—North America was separated from South America by some sort of a water barrier until rather late Cenozoic time. That left South America as an isolated region and peculiar types of animals evolved there, entirely independent of the animals of other regions. Some remnants of this development are still present in South America; it is there that the tree and ground sloths—clumsy, awkward, stupid creatures—occur. Huge birds of peculiar types, some of which reached a height of 7 or 8 feet and were wingless, appeared late in the era and lived almost to the present.

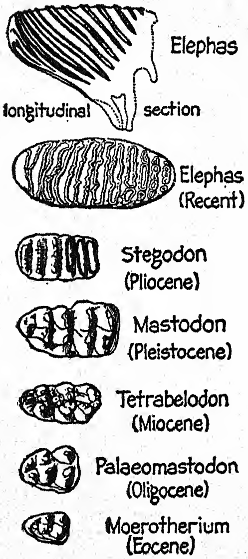


FIG. 446.—Types of elephant teeth, showing evolution in size and in type of grinding surface. (*After Moore, modified from Lull.*)

Late in the Cenozoic when land connection was established between North America and South America, some of the South American animals came into southern United States, and among these were the sloths. A very large armadillo-like animal had flourished in South America and it came as far north as the Missouri River. It was described by Thomas Jefferson, who seems to have been the only president of the United States who ever dabbled in paleontology. He found remains of this animal in North Carolina, collected them, and named the species. The North American mammals went southward into South America and mingled with the South American forms. The ill-adapted South American types never gained much of a hold in North America.

Isolated Areas.—Islands and other isolated areas are favorable for the origin of peculiar types. This is strikingly brought out by Alfred Russell Wallace in his book called "Islands and Island Life." Darwin was greatly impressed by the development of peculiar types in the Pacific islands. In Australia many types of primitive mammals developed.

Aquatic and Flying Mammals.—In the evolution of the reptiles of the early Mesozoic you will recall how some forms took to water and developed swimming appendages, others to the air and developed wings, some became climbers, and others burrowers. Parallel development took place among the mammals in early Cenozoic. Mammals with wings,

such as the bat type, came in early but were always rare. Flying mammals never reached the importance of flying reptiles, and they are among the rarest of all fossils. The water has always been a favorite

FIG. 447.—An upper Oligocene group of mammals and plants. In the background are three titanotheres, the largest mammals of the times; in the middle distance are giant piglike animals; four small even-toed ungulates are in the lower foreground; at the left is a primitive cat; in the right foreground an oredon, a generalized browsing mammal.

habitat and no sooner does evolution of a particular group start than some of them become water livers. The continental deposits that we have been considering did not furnish favorable surroundings for animals

to adapt themselves to water living, but where the seas came up over the land on the Atlantic and Gulf Coasts the mammals had ample opportunity to take to the water. Before the close of the first Cenozoic period several types had so adjusted themselves as to be entirely at home in the water. Primitive whales inhabited the water along the Atlantic and Gulf Coasts and in a comparatively short time they developed into very large animals.[1]

Many other types of swimming mammals were developing throughout the Cenozoic. Everyone is familiar with several of the modern descendants, such as seals, sea lions, and walruses. As with the reptiles, the adaptation to living in the water was best shown in the modification of the feet and legs, which became paddles. In some cases the legs degenerated into entire loss and the animal swam mainly by means of the tail. No air-breathing animal has evolved water-breathing apparatus.

Fossil Fishes.—When the Union Pacific Railroad was built through western Wyoming, numerous fossil fishes were found in the Green River formation of the Eocene in one cut and the place was named "Fossil" on that account. Ever since that time these fossil fishes have been an object of curiosity for tourists and have been sold at various towns along the railroad. At the present time one man makes it his business to quarry out these fishes and sell them. The fishes are preserved in a very fine-grained limestone which probably was formed as a chemical precipitate on the lake floor. Every detail of the structure of the hard parts is preserved and they occur in such quantities that a person knowing nothing about them can collect many fragments if he happens to go to the right place. The rock is quite different from the lithographic limestone of Bavaria which we have considered as very favorable for the preservation of fossils.

The fishes from the Green River formation are much like modern fishes, indicating that most of the evolution of fishes had taken place before this early stage of the Cenozoic. However, the differences are great enough to make all of them of different species from those of the present. Along with the fishes occur huge palm leaves and parts of other subtropical plants; evidences that the climate was considerably

[1] The bones of fossil whales were objects of curiosity to early settlers in the Carolinas and were interpreted as remains of huge animals that had succeeded in reaching those places at the time of the Deluge. One enterprising citizen collected and put together bones enough to make an animal about 125 feet long. With these he traveled over the country, displaying "the great reptile," as he called it, for an admission fee. He named the animal Basilasaurus. He finally took the specimen to England where it was purchased by the British Museum. Experts there found that several animals were represented in the one specimen. The owner had collected as many bones as he needed and put them together to make an animal of large size for exhibition purposes. The experts also found that the animal was not a reptile, as was indicated by the name Basilasaurus, but a primitive whale, and it was renamed in accordance with its true nature.

warmer during that period than at present. Fossil insects are abundant in the same beds as the fishes.

Climate.—The climate of the Cenozoic fluctuated considerably Evidences of glaciation have been found in Eocene deposits of Colorado; in the Green River deposits of the same period in western Wyoming subtropical plants were abundant. Coal formed in Alaska and in islands within the Arctic circle. Fossil palms have been found in Greenland. In Pliocene the climate became cooler and that epoch closed as the great continental glaciers spread over the continents. Within the glacial epoch climates became so mild during glacier retreats that subtropical plants grew as far north as southern Canada. The glaciers disappeared and at present we do not know whether climate is growing colder or warmer, drier or wetter.

Economic Products.—The Cenozoic is the period of greatest oil production in North America. Most of the oil comes from California, Texas, and Louisiana. A great deal of coal formed in the early Cenozoic in northwestern United States but little is mined. The igneous intrusion of the period gave rise to many rich deposits of gold, silver, copper, lead, zinc, and other metals.

CHAPTER XXVII

THE PLEISTOCENE OR GLACIAL EPOCH

The geological epochs, except the Pleistocene now under consideration, are all based on advances and retreats of the seas. After the last important sea invasion there came such marked changes of climate as to result in extensive glaciation in many middle latitudes of the world. When this was first realized, it was supposed that here was the first extensive glaciation that had taken place in geologic time and that it constituted a real geologic period. Had the earlier glaciations been known, as they are now, it is probable that the Pleistocene would have been considered as merely an epoch of another period.

Glaciers Form.—The Pleistocene was initiated by decrease in temperature, particularly in the northern hemisphere. This decrease gradually brought on an excess of snowfall over waste in the northern half of North America and Europe. This excess could occur only where the amount of snowfall was considerable. Glaciers do not form in arid regions no matter how cold. In North America the glaciers advanced southward from three centers of dispersion and at their greatest extent they reached to about the Missouri and Ohio Rivers. The front of the glacier extended from Long Island to the Rocky Mountains of northern Montana. The ice edge was not regular but resembled a somewhat regular seashore.

In Iowa five epochs of glaciation have been recognized by the presence of five drift sheets. Five times glaciers covered all or part of the state, and five times they melted away. Between some drift sheets there was more weathering than has taken place since the last ice retreat, indicating that the time between ice retreat and readvance was longer than the time since the last glaciation.

Indications of two to five ice advances have been found in many places in North America and students of glaciation recognize five glacial epochs in the Pleistocene. The oldest glacier of the Pleistocene seems to have been one of the most extensive and to have advanced more than 1,000,000 years ago. The last glacier withdrew from the Niagara Falls region 40,000 to 50,000 years ago if our Niagara Falls timepiece is to be trusted.

Ice Covers Mountains and Enters the Ocean.—The ice of the main glaciers must have been 4,000 or 5,000 feet thick in the centers from which it advanced, and it must have thinned to less than 100 feet at the edge.

Many of the New England mountains were covered by ice and also the Adirondacks in New York and various ranges in Canada. Along the New England coast and part of New York the ice pushed out into the shallow part of the ocean and built its terminal moraines under the sea. It left the area over which it advanced mantled with ground or terminal moraine and dotted with lakes ranging in size from Lake Superior down to mere ponds. It left waterfalls and streams entirely out of adjustment

Fig. 448.—Map of North America showing area covered by glacial ice during some part of the Pleistocene epoch. (*From W. C. Alden, U. S. Geol. Survey.*)

with the underlying solid rocks. All of the Great Lakes were formed largely by glaciation, mainly by filling and irregular damming of old valleys but in part by scouring.

The Great Lakes.—The history of the lake region from the time when the last glacier retreated so as to allow the lakes to begin to form, is well known. The first outlets were south, from Lake Erie and Lake Michigan to the Ohio and Mississippi. The Chicago Drainage Canal, which carries the sewage from Chicago, was excavated in one of these old outlets. At a later stage of ice retreat a lower margin was uncovered, the one through which the waters run over the Niagara Falls.

During this history the margins of the lakes changed considerably and some of the lakes remained at different levels long enough to create old beaches and even well-developed sea cliffs and wave-cut terraces. South of Lake Erie and Lake Ontario old beaches and barriers may be followed for many miles. The first railroads in northern Ohio were built on the old beaches. The first wagon roads also followed these beaches and the farmhouses were built near them. Away from the beaches the mantle rock was largely lake deposits of silt and clay and made road construction very difficult. Silt and clay might be 10 feet or more thick and when wet formed a deep mud, with the result that vehicles mired down. The beaches and barriers were built of sand and gravel and made

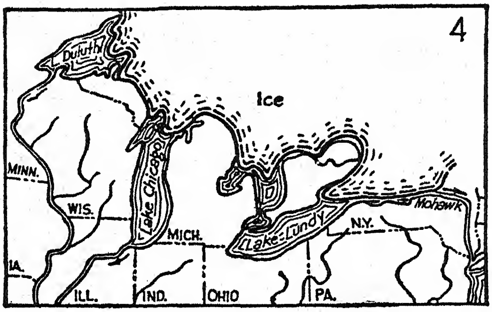


FIG. 449.—A late stage in the formation of the Great Lakes. (*From Taylor and Leverett, U. S. Geol. Survey.*)

natural roads. The results of these earlier selections of places for roads are still apparent. Villages are along the old beaches and the main roads are still there.

Glaciation and Economic Development.—The effect of glaciation on early settlements is shown by other trade routes. The Erie Canal would probably never have been undertaken had it not been that the valley was once occupied by a stream draining the Great Lakes. A canal running from the west end of Lake Erie southwestward through Ohio and Indiana follows an old outlet valley. Cleveland became a railway center because of preglacial valleys through the highlands to the southeast. These valleys were abandoned by their streams with the readjustments of drainage that came about when the glacier retreated. Niagara Falls were caused by changes of drainage brought about by glaciation and the great electric plants developed there owe their location to glaciation. The side of a great valley was formed in the Paleozoic rocks east and west of Niagara. The tributary streams to this valley were in harmony with the main stream and had cut through the side cliffs so that they emerged into the main valley at the level of the main stream. The glaciers filled up the old valleys with drift and a new stream draining Lake Erie took a new course, after the glaciers retreated, through the lowest place over the glacial topography. This new drainage stream

missed the old valleys, came to the cliff over high land, and thus formed the original Niagara. If it had happened to strike through one of the preglacial valleys, the entire history and development of that part of the United States would have been different.

Old Lakes Filled with Peat.—Nearly all of the peat bogs of Canada and of northeastern United States originated in glacial lake basins. The peat bogs of Ireland and of western Europe also developed from such lake basins. We do not think of glaciation as forming a condition favorable for the beginning of coal beds, but the peat bogs could become filled, the peat covered with silt and sand, and in course of time become coal. Such coal beds are, in the main, small and irregular, and do not compare in thickness or extent with the coal beds of late Paleozoic or late Mesozoic time. However, in Ireland and western Europe peat is used extensively as fuel and the peat bogs are of real value to the inhabitants. In New Jersey peat is gathered, cut into briquets, and used as fuel. Some of the old bogs that have filled partly with plant remains and with clay are used for growing garden truck, particularly celery. The celery gardens of New Jersey and eastern New York are largely in these old bogs.

In some places, however, the bogs are not advantageous to man. Some of the earlier railroad builders, particularly in Canada, had great trouble from them. The railway engineers did not realize the character of the material and so built railroads directly across the bogs or muskegs, as they called them. As soon as the railroads were used, the tracks began to settle. In spite of the use of thousands of tons of rock as ballast, they continued settling, in many cases compelling relocation so as to go around the bogs.

Western Lakes.—Some other lakes of Pleistocene and later times should not be passed without mention. Great Salt Lake was a body of fresh water many times as large as at present. It drained northward into Snake River through a valley that has been little changed since the stream ceased to flow through it. Along with increase in temperature in the Rocky Mountain region, decrease in precipitation must have come, for Great Salt Lake has actually dried down to its present state. That means that it has changed from a lake covering 20,000 square miles to one covering less than 2,000, from extreme depths of more than 1,000 feet to average depth of less than 20 feet, and from normal river water containing only 1 part common salt in 20,000 parts of water to 1 part common salt in 30 parts of water. Other salt lakes of the same kind were present in the Rocky Mountain region and westward, but Lake Bonneville, the ancestor of Great Salt Lake, was the largest and most important. Lake Agassiz, another very large Pleistocene lake, covered considerable areas in Canada, Minnesota, and North Dakota. It was shallow and was nearly filled with sediments, mainly sand and coarse

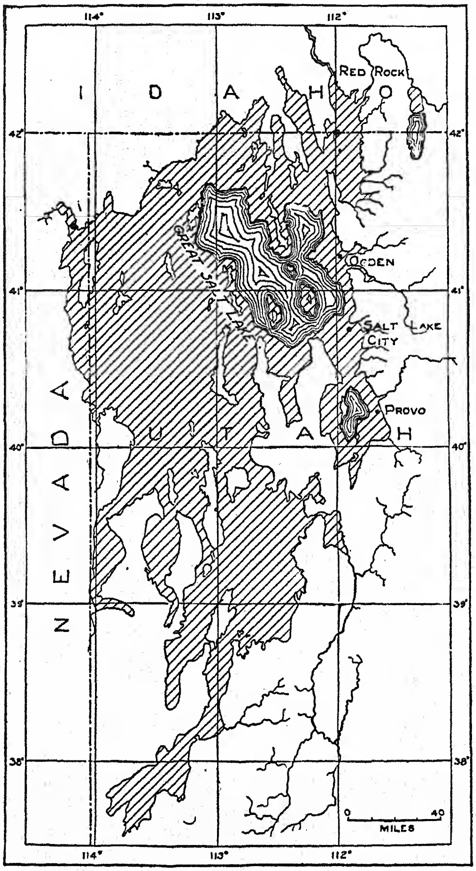


FIG. 450.—Map of Great Salt Lake showing its relation to the vast ancestral fresh-water lake known as Lake Bonneville (shaded). (*After Gilbert, U. S. Geol. Survey.*)

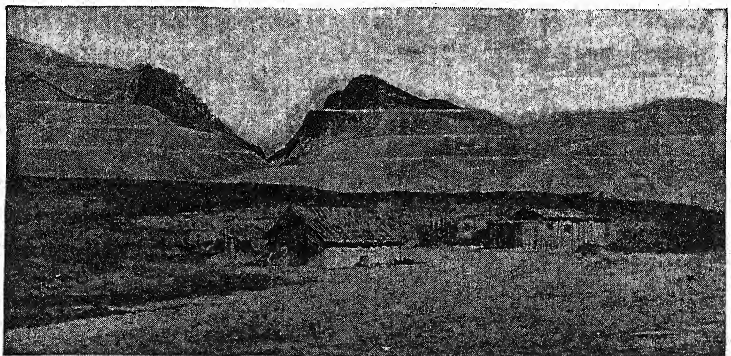


FIG. 451.—Ancient shore-line terraces of Lake Bonneville. (*After Gilbert.*)

clay, before it was drained by the lowering of the northern outlet upon withdrawal of the glaciers. The deposits cover nearly flat areas that constitute the extensive wheat lands of the region where the lake existed. At one time this lake drained southward into the Mississippi, but with the disappearance of the ice at the north the northern margin became lower than the southern and it drained northward into the Mackenzie River.

Valley Glaciers.—While the continental glaciers covered so much of the northern part of America, Alpine glaciers were much more extensive in the mountains than they are at present. Glaciers 25 miles long stretched out on to the plains from the Uinta Mountains in Utah, where no glaciers now exist. Every mountain range of the Rocky Mountains and westward presents similar phenomena. From the eastern slope of the Rocky Mountain front ranges in Montana and northern Wyoming some distance intervenes between the moraines of the mountain glaciers and those of the continental. The Appalachian Mountains were not high enough to have local glaciers.

Boundary of Glaciated Areas.—As described in the chapter on glaciation, the margin between the glaciated areas and nonglaciated is not well marked in all places, the oldest glacial deposits having been so greatly eroded by streams that none of the original glacial topography remains. Under such conditions the former presence of glaciers can be recognized only by the presence of materials from remote regions in places where they could not have been deposited by streams. This is the case, particularly along the margins of the old drift in Kansas and Missouri, near the Missouri and Kansas Rivers.

Soils correspond in a general way to the underlying rock where the soils have not been transported. In glaciated regions soils are irregular and do not correspond in any way to the underlying rocks. A good soil map is likely to show the contact of glaciated and nonglaciated areas by the soils represented.

Drift Becomes Solid Rock.—The wide occurrence of glacial drift over North America and the similarity of the drift from one place to another allow its recognition with very little question. This is a continental deposit as widespread as many of the rock deposits that were formed beneath the sea, which geologists trace over very wide areas, and which with their fossil contents form the basis for working out historical geology. With the progress of time much of the drift is likely to be washed away by streams and reworked to form stream, lake, and ocean deposits. If it should happen that seas should advance over the area where the drift is present and should deposit other sediments over the drift it might become cemented, change to solid rock, and be preserved. In Canada this solid rock might be on pre-Paleozoic deposits, in New York on Paleozoic, in Montana on Mesozoic, in some other place on

Cenozoic, and its age could not be determined from the rocks on which it lies.

How to Determine the Age of Drift.—If the Pleistocene consolidated drift in Canada should happen to overlie the pre-Cambrian consolidated drift, the two might be so much alike as to make the distinguishing of them difficult. The materials for both would have come from the pre-Cambrian rocks, and glaciers in the pre-Cambrian must have made their deposits in the same way as they did in the Pleistocene. There is some likelihood that the pre-Cambrian drift would be somewhat metamorphosed, but in the event that neither was metamorphosed beyond the stage of being firmly cemented they might be indistinguishable. It would be possible that the pre-Cambrian drift had been entirely eroded away from one place and Pleistocene drift deposited directly on granite or pre-Cambrian schist or gneiss. In a near-by area it would be possible that the pre-Cambrian drift would lie on the same kind of rocks and there be no Pleistocene drift over it. The geologist working in the field would find it difficult, then, to tell the age of the two drifts. Either might be Pleistocene, either might be pre-Cambrian. One fossil might serve to solve part of the problem. If even a fragment of bone were found in the drift it could not be pre-Cambrian, as animals with bones did not live at that time. A mastodon tooth, a mammoth tooth, the tooth of a horse, or any recognizable bone of Pleistocene mammal would be adequate proof of age. However, if the age of one drift were proved in this way, and no fossils were found in the other, the other would not on that account be pre-Cambrian. It might be Pleistocene but nonfossiliferous. The Pleistocene drift would be difficult to identify from one locality to another on the basis of fossil content, because fossils are so rare. Conditions for burying and fossilization of animals were not favorable.

It might be possible to solve the question of the age of the drifts by tracing them laterally. If one could find Paleozoic rocks overlying one drift and underlying the other, he would then have proved the wide difference in age of the two, and as only the two series of drifts have ever been found in southern Canada, he might assume with a considerable degree of certainty that the one drift is pre-Cambrian and the other Pleistocene.

Glaciation and Plants.—As the margin of the glacier moved northward, plants covered the ground left bare by the retreating ice, but at times the ice retreat was fast enough to leave great areas of barren ground exposed. Some geologists suppose that such barren ground, covered with the mixed glacial flour and weathered material, furnished the winds with the fine material that finally formed the loess. As you will recall, the loess contains a large amount of nonchemically weathered fine material and this could originate from the ground-up rock of the glacier.

The fluctuation of temperature between advances of the ice went beyond what we now consider normal. In some of the interglacial stages plants of types that grow no farther north than Florida at the present time grew in southern Canada. That is, southern Canada, seemingly, was subtropical. It is possible that we are now living in an interglacial stage, although there is no sure evidence to show that such is the case. As has been pointed out, most glaciers are retreating at the present time, indicating either a lessening of the amount of precipitation or a rising of temperature. However, even the retreat of the glaciers does not show that we are living in an interglacial stage. The climate has not become so warm as it was in some interglacial stages of the Pleistocene.

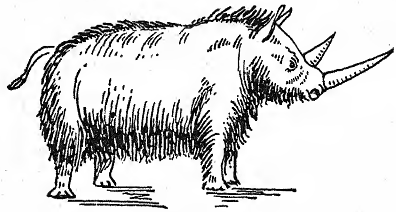
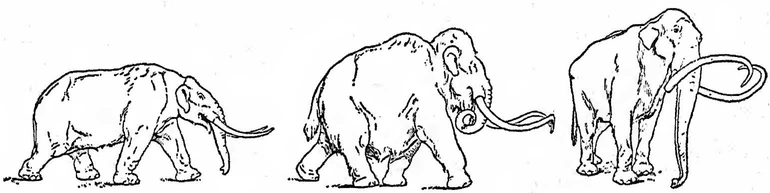


FIG. 452.—A Pleistocene woolly rhinoceros.



(a) (b) (c)

FIG. 453.—(*a*) Pleistocene mastodon, (*b* and *c*) Pleistocene mammoths. (*After Scott.*)

Glaciation and Animals.—Glaciation had profound effects on the life in and beyond the glaciated regions. As cold came on and glaciers advanced from the north the warmth-loving animals and plants migrated southward. Many of the plants were destroyed. Animals that could not adjust themselves to increasing cold gradually disappeared or came to inhabit only the more southerly areas. Some animals lived at the margins of the glaciers or inhabited the hills that stuck up through the ice and some developed protective coverings. The woolly rhinoceros and the hair-covered mammoth lived on the glaciers and along the glacial margins.

FIG. 454.—A giant sloth from the Pleistocene.

In general the animals and plants of the Pleistocene were not greatly different from those of the present, although some of the more prominent animals died out.

In North America many species of horses, deer, antelope, buffalo, bear, cats, and dogs of various types mingled with some boreal forms and

some tropical forms, and they moved northward with the coming of the warmer climate. The mastodon and mammoth were common until after the retreat of the last glacier from the United States. Their remains have been found in bogs of the last moraines. Horses were rather abundant, but they disappeared from North America between the time of the retreat of the ice and the coming of Europeans. The disappearance of horses, mammoth, and mastodon is hard to explain. The mammoth lived to within a relatively recent time. Its remains with flesh intact have been found frozen in the ice of Siberia.

MAN

The Pleistocene epoch might be called the time of the rise of man to dominancy. We are naturally much interested in the history of man, but from the geological point of view less is known of him than of most

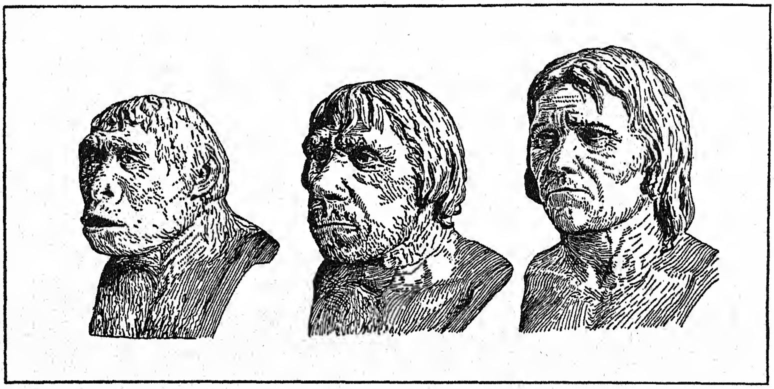


FIG. 455.—Restorations of Pithecanthropus, left; Neanderthal man, middle; Cro-Magnon man, right. (*Permission of American Museum of Natural History.*)

other animals. Man's history has been worked out only from imperfect, widely scattered specimens, whereas the well-known horse history is based on thousands of fossils.

Pithecanthropus, the Ape Man of Java.—In 1892 a specimen was discovered in Java which seemed to be intermediate between the highest type of ape and man. Apes have large brain capacity compared to their size, but the proportion is very much less than in man. Man's brain capacity is greater than that of any other animal in comparison to his size. The Java specimen does not have the brain capacity of man but seems to have greater brain capacity than any ape. As a matter of fact only part of the skull of the "Java man" is known and measurements of brain capacity vary to a considerable extent. The teeth of the Java specimen are somewhat more like those of apes than of man. Only one limb bone is known, a femur, and it indicates an erect-walking creature, much more like man than ape. It is not known that all of the

associated bones belong together, so that though this creature is known as "the ape man of Java" there are so many uncertainties concerning it that it does not help very much in tracing the descent of man.

As far as can be determined, the Java remains came from the Pliocene, the epoch immediately preceding Pleistocene, and they constitute our earliest record of man if the creature was really man.

The Heidelberg Man.—The next oldest remains were found in Germany, near Heidelberg, and consist of one lower jaw. The jaw is heavy and retreating, and the teeth are much more primitive than those of modern man. They are not ape-like and by no stretch of the imagination could the jaw be considered as belonging to anything but man.

The Piltdown Man.—In 1911 part of a skull was found in a gravel pit near Piltdown, England, and near it but not associated with it a tooth and some other bone fragments. The skull is primitive in many respects and the teeth also are considerably different from those of modern man. The brain capacity, so far as can be determined, is smaller than that of ordinary man, although not smaller than the smallest brains known among modern people. As the remains were scattered, it was not possible to determine the position of some of the teeth. Had this not been the case the specimen might have helped to solve the problem of the relationship of the remains to those of modern man.

The Peking Race.—In 1928 fossils of man more advanced than the Pithecanthropus were found near Peking, China, and since then several other finds have been made. At the present time paleontologists are not agreed as to whether the race represented by the Peking fossils is older or younger than the Piltdown race. The Piltdown man seems to have lived about the third interglacial stage and the Heidelberg man probably the second interglacial stage. In the fourth interglacial stage cave-dwellers had established themselves in western Europe and their remains are rather well known. All are plainly types of men comparable to some of the types of the present time.

Ancestors of Man.—The Neanderthal men, as they are called, throw no light on the way of man's development. The Grimaldi, a negroid type that lived at the same time, was not in the line of development of modern man and cannot be considered directly ancestral to modern man. Another race known as the Cro-Magnon was one of the finest physically that ever lived. They were large, had large brain capacity, and their civilization had progressed to a high stage. It was they who painted in colors the well-known pictures in some of the ancient caves of France. But none of the three types gives any real clue as to the descent of modern man. We are left with the firm conviction, the certainty as a matter of fact, that man has developed from lower animals in the same way that other modern animals have developed from ancient forms, but

we do not know the precise steps in the development of man or from what ancestor he came.

Man's way of taking care of his dead has made him the rarest of all fossils, and though it is likely that more fossils of man will be found and probable that man's ancestry may be roughly traced at some time, at present we must consider the matter as unsettled and allow the future to take care of the problem.

Pleistocene Man in Europe.—In western Europe man was a cave dweller during the late Pleistocene. Not only his bones but his implements and drawings have been found in the caves and in deposits below glacial drift in other places. In the caves his bones are associated with those of the cave bear, saber-tooth tiger, mammoth, and other Pleistocene animals, and his drawings depict Pleistocene species. The drawings are more convincing than the bones, as man's bones might have become mingled with older bones in the caves, but he could not have drawn animals that he had never seen. Artifacts such as were found in the caves have been found in interglacial deposits at no great distance from the caves and constitute a means of matching the cave time with glacial time.

Pleistocene Man in America.—Man was present in Europe during the later part of the glacial period and probably during the earlier, but it is still a point in question as to whether he was present in America. Many finds of implements made by man and of actual human bones have convinced some investigators of his presence before the last ice advance, but in every case there has been enough uncertainty to leave the less easily convinced skeptical. No scientist says that man was not present in America during the Pleistocene, but the burden of proof still remains on those who are to prove his presence.

We may raise the question as to what would be sufficient evidence of his presence. At Vireo, Florida, bones of man were found with those of animals that lived only during the Pleistocene. They were not very far below the surface, and some investigators said that they might have gotten mixed up with the bones of the Pleistocene animals by falling into a hole where a tree had been uprooted from above the deposits which contained the other animals, or by a small stream cutting a little valley through the deposits and the valley becoming filled by deposits in which the bones of man were preserved and the other bones weathered in from the sides or carried in from a short distance away. Or it was possible that all of the bones had been carried and deposited in that place later than Pleistocene times. The Vireo deposit is evidence in favor of man being present at the same time as the other animals, but it is not absolutely convincing.

Near Lansing, Kansas, human remains were found below some 40 feet of river deposits, and for a time this was held as proof of man's early

occupancy of America. But students of river deposits soon pointed out that the river may shift its deposits very quickly and that 40 or 50 feet of sand and clay could be piled up in one place within a few years.

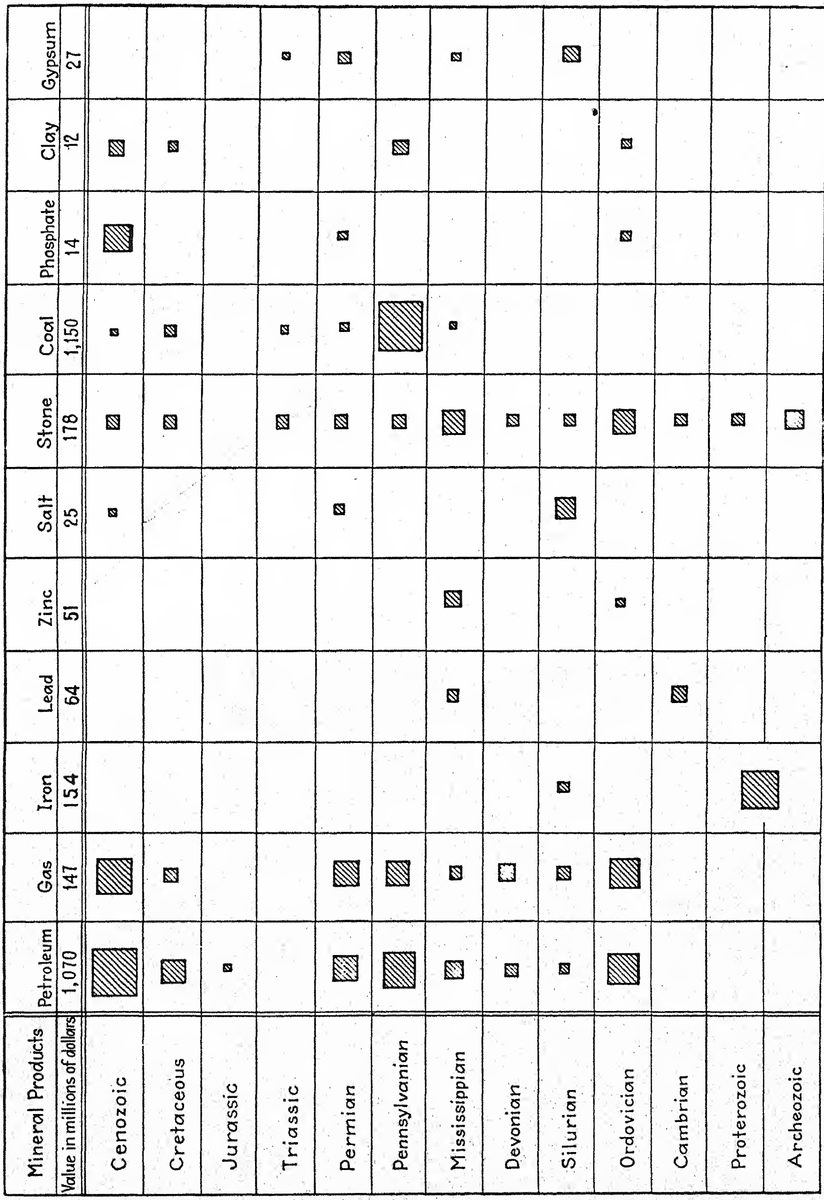


FIG. 456.—A table showing age of rocks containing various mineral deposits. As the age given might be misleading, several mineral products are omitted from the table.

Recently in Oklahoma the remains of man have been found in seemingly undisturbed sediments along with bones of mastodon and other animals not known to have lived beyond the Pleistocene. These

finds, too have not proved convincing to some geologists, and the question still remains open, although evidence seems to point more and more positively toward man's early occupancy of America. The finds in Oklahoma are outside of the glaciated area, and so are not associated with glacial deposits. When man's implements or bones are found below a considerable thickness of undisturbed glacial drift, *i.e.*, where there can be no question of their ever having been moved, geologists will be completely convinced of the presence of man in America during the Pleistocene.

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